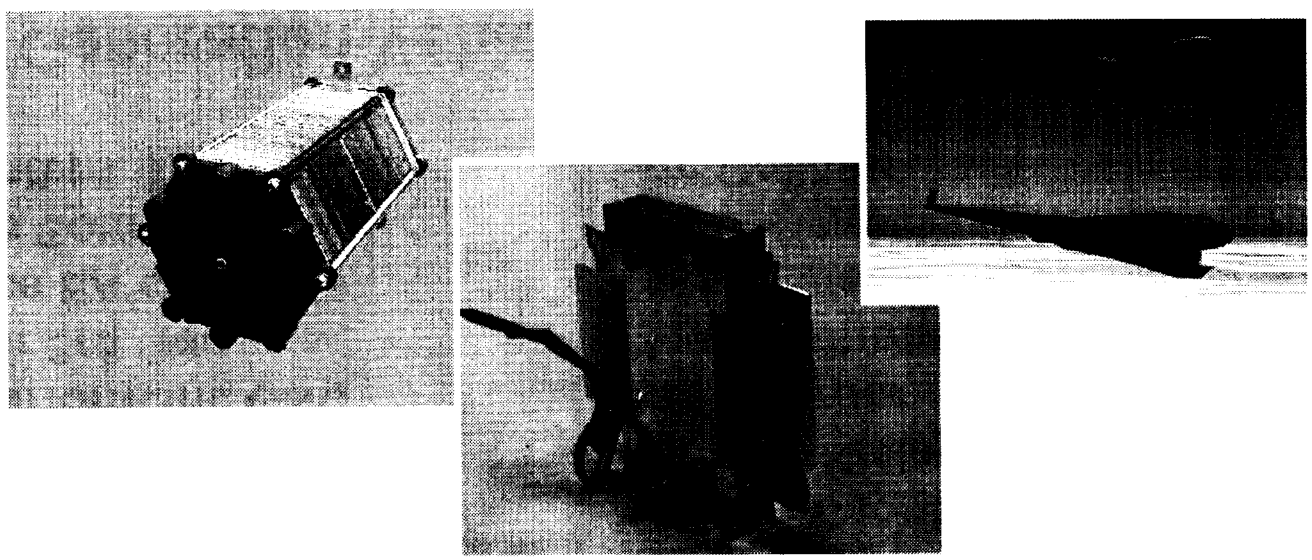
5-3

112 p

2nd & 3rd Generation Vehicle Subsystems



"ST Day 2000: Reducing Risk for the Next Generations"

♦ 3rd Generation Vehicle Subsystems

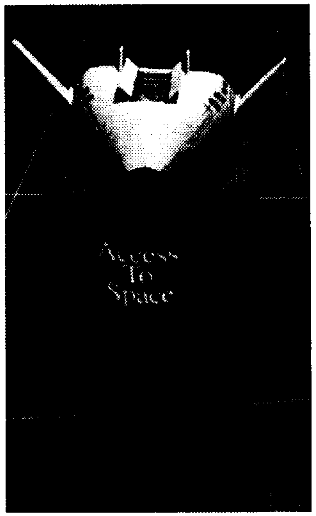
Project Overview	Scott Jackson	8:00 - 8:10
University (Cornell U.)	Kathryn Caggiano	8:10 - 8:30
SFINX	Anthony Kelley	8:30 - 9:00
High Performanc G&C	Dan Moerder	9:00 - 9:30
EHW for 3rd Gen.	Wayne Schober	9:30 - 10:00
Advance EA's	Jose Davis	10:00 - 10:20
Hybrids Sources	Jeff Brewer	10:20 - 10:45
Intell. Intern. Therm. Ctrl.	Eric Golliher	10:45 - 11:00

♦ 2rd Generation Vehicle Subsystems

Project Overview	Mike Skor	11:00 - 11:20
PEM Fuel Cell Project	Mark Hoberecht	11:20 - 11:50
Wrap up	All	11:50 - 12:00

Agenda

- ## Earth-to-Orbit :



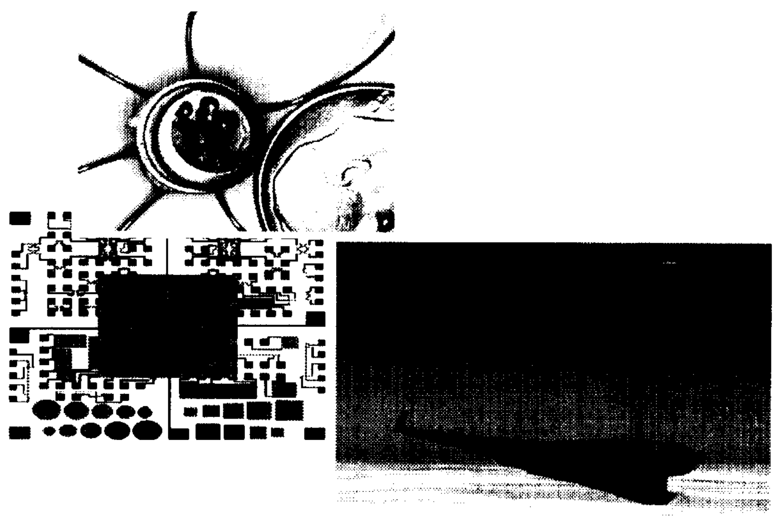
GOALS 9

<u>Low-cost Space Access</u>:

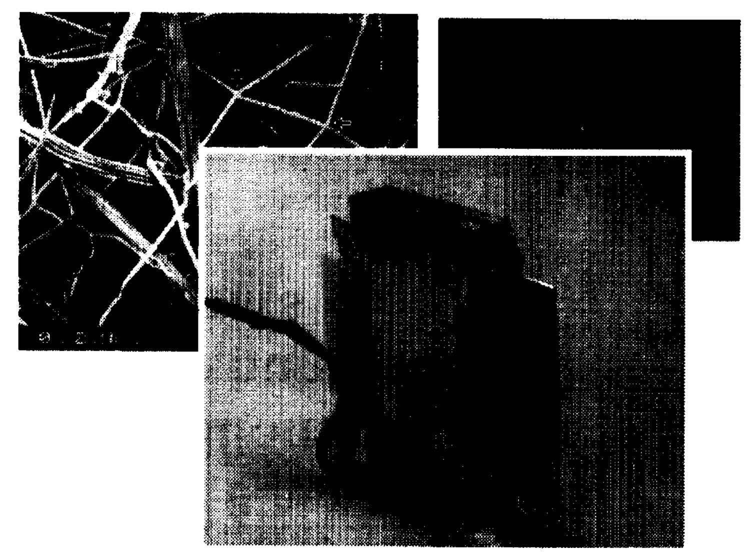
Reduce the payload cost to orbit by an order of magnitude, from $10,000 to $1,000 per pound, within 10 years and by an additional order of magnitude, from thousands to hundreds of dollars per pound, within 25 years

- ## Launch Technology Project
  - Provide basic launch technology building blocks to enable significant improvements in safety and reliability of transportation systems while reducing the life time cost.

- **Technology Objectives:**
  - **Design, develop and test advanced avionics, power systems, power control and distribution components and subsystems for insertion into a highly reliable and low-cost system for a reusable launch vehicle.**



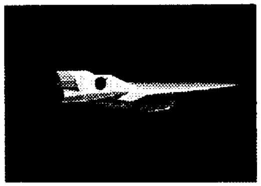
Avionics and Flight Control
Lead Center - MSFC

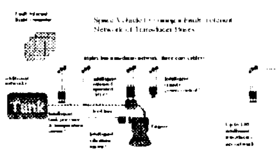


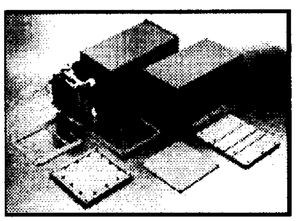
Power
Lead Center - GRC

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Vehicle Subsystems Project, 3nd Gen







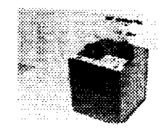
Project Manager
Scott Jackson
MSFC

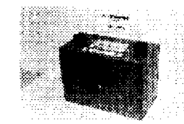
Avionics
Lead Engineer
Anthony Kelley
MSFC

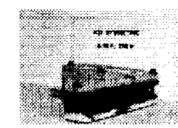
- University Studies
  Anthony Kelley
  MSFC
- SFINX
  Anthony Kelley
  MSFC
- EHW for 3rd Gen.
  Wayne Schober
  JPL
- Robust Low Cost Avionics
  Shawn Wallace
  MSFC
- High Perf, G&C Adpt.
  Dan Moerder
  LaRC

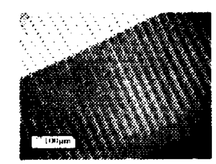
Power
Lead Engineer
Jose Davis
GRC

- Advanced EA's
  Mary Roth
  GRC
- Hybrid Sources
  Linda Taylor
  GRC
- High Temp Pwr Electronics
  Gene Schwarze
  GRC
- IITC
  Eric Golliher
  GRC









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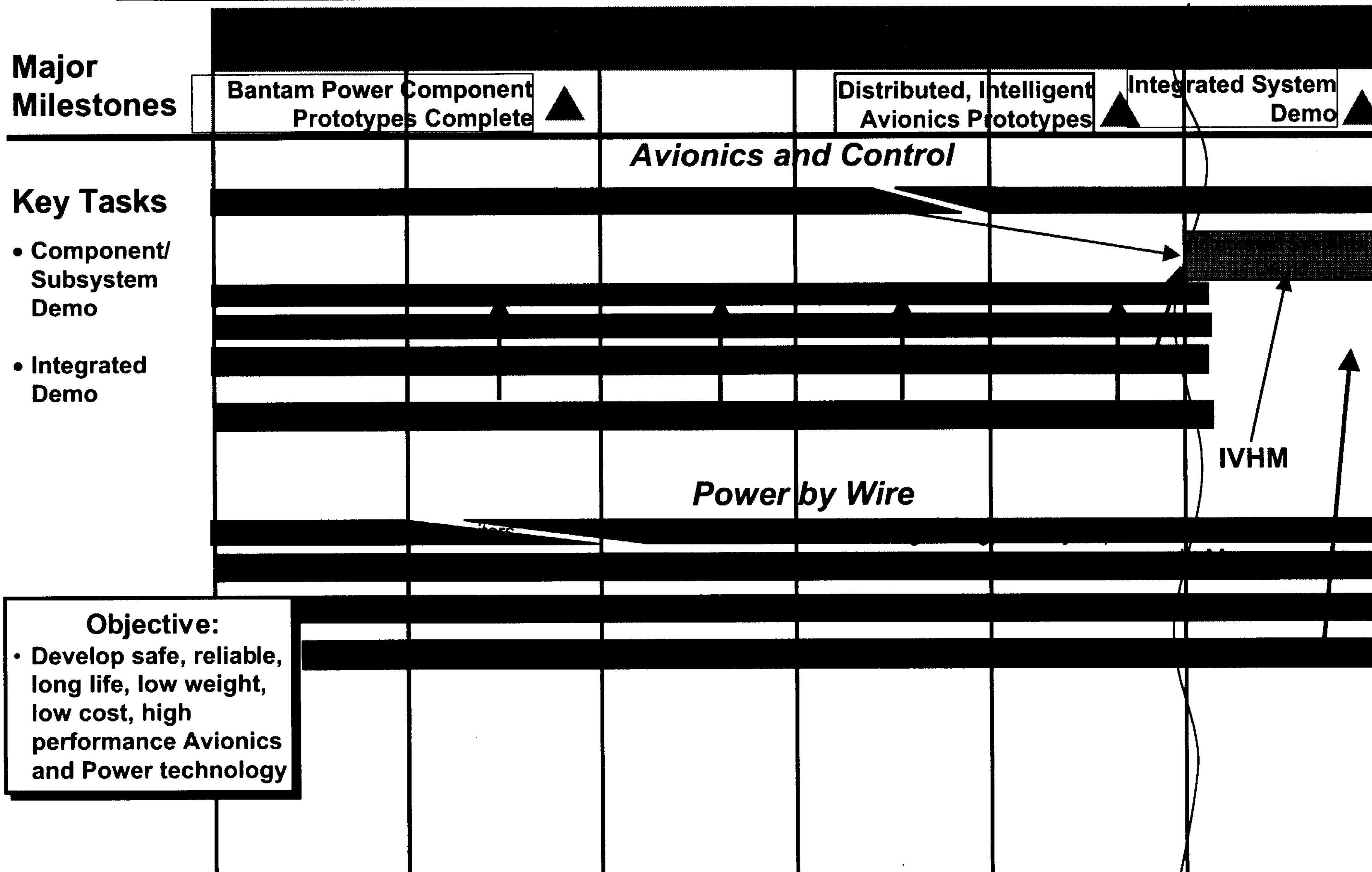
3rd Gen. Project Management Structure

- Achieve 100% Reliability
- Increase Safety
- Operate In Any Environment
- Achieve Near Zero Mass Systems
- Increase Operability & Maintainability

3rd Gen. Technical Challenges

3rd Gen. Launch Technology Roadmap



"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

NAME	ORG.
Anthoney Kelley (Lead)	MSFC
Charles Hall	MSFC
Mike Watson	MSFC
Mike Goode	LaRC
Dan Moerder	LaRC
Gary Hunter	GRC
Bill Espinosa	GRC
Chuck Jorgensen	ARC
Wayne Schober	JPL
Leon Alkalai	JPL
Nikzad Benny Toomariab	JPL
Jean- Pierre Fleurial	JPL
Kevin Wheeler	ARC
Ray Garbos	Lockheed
Bruce Powel Douglas	Private

3rd Gen. Avionics Technology Working Group

NAME	ORG.
José M. Davis (Lead)	GRC
Nang T. Pham	GRC
Mary Ellen Roth	GRC
Gene Schwarze	GRC
Eric Golliher	GRC
Steve Luna	MSFC
Steve Ryan	MSFC
Mark King	MSFC
Rao Surampudi	JPL
David Homan	Wright Lab
Russ Spyker	Wright Lab
Jerry Beam	Wright Lab
Joe Weimer	Wright Lab

- University Studies (Cornell University)
  Kathryn Caggiano (Cornell University) (607) 255-0698

- High-Performance G&C Adaptation
  Dan Moerder (LaRC) 757-864-6495 d.d.moerder@larc.nasa.gov

- Evolvable Hardware (EHW) for 3rd Generation Avionics Description
  Wayne Schober (JPL) 818 354-8581 wayne.r.schober@jpl.nasa.gov

- SFINX Scaleable, Fault-tolerant Intelligent Network or X(trans)ducers
  Anthony Kelley (MSCFC/ED12) 256-544-7646 anthony.kelley@msfc.nasa.gov

- Advanced Electric Actuation Devices and Subsystem Technology
  Jose Davis (GRC) For:
  Mary Roth (GRC) 216-433-6288 Mary.E.Roth@lerc.nasa.gov

- Hybrid Power Sources and Regeneration Technology for Electric Actuators
  Jeff Brewer (MSFC) For:
  Linda Taylor (GRC) 216-433-3370 Linda.M.Taylor@lerc.nasa.gov

- Intelligent Internal Thermal Control
  Eric Golliher (GRC) 216-433-6575 Eric.L.Galliher@lerc.nasa.gov

3rd Gen. Subsystems Presenter Contact Info.

Supporting the NASA RLV Program

Kathryn E. Caggiano
Peter L. Jackson
John A. Muckstadt

Cornell University
Operations Research and Industrial Engineering

"ST Day 2000: Reducing Risk for the Next Generations"

Develop analysis tools for determining and evaluating spare parts stocking policies for components of Reusable Launch Vehicles

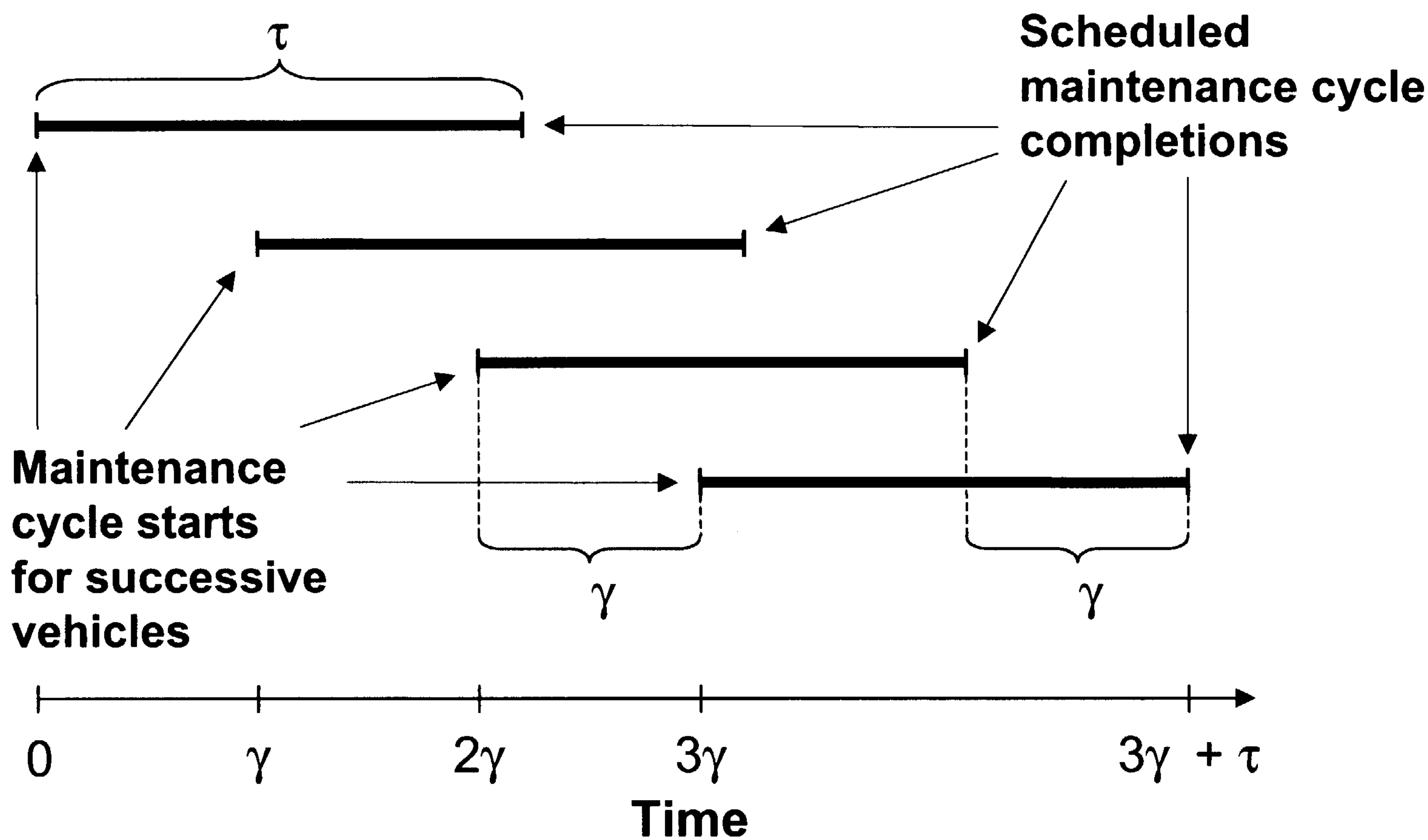
Cornell Project Objective

- System Framework
- Analysis Tools
- Analysis Process (GEM)

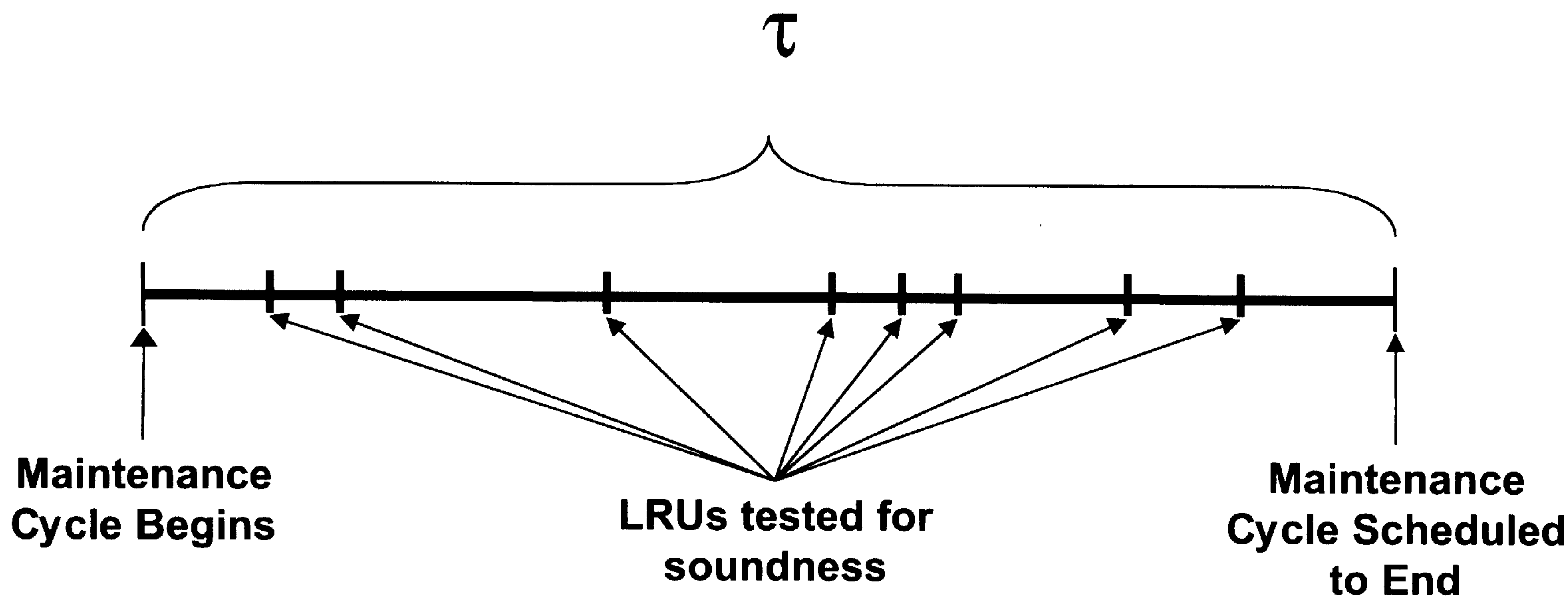
Overview

- RLV Ground Maintenance Process
- Line Replaceable Unit (LRU) Repair Process
- Shop Replaceable Unit (SRU) Repair Process

System Framework

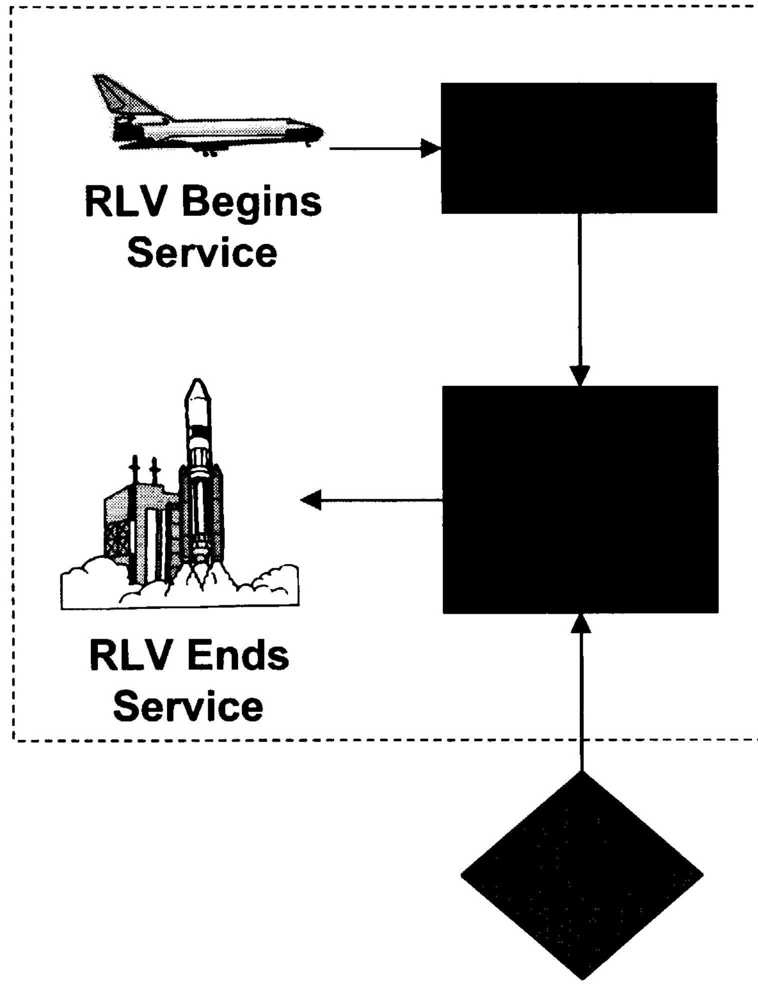


RLV Maintenance Cycles



Failed LRUs must be replaced by the scheduled end date in order to avoid a delay.

One Maintenance Cycle



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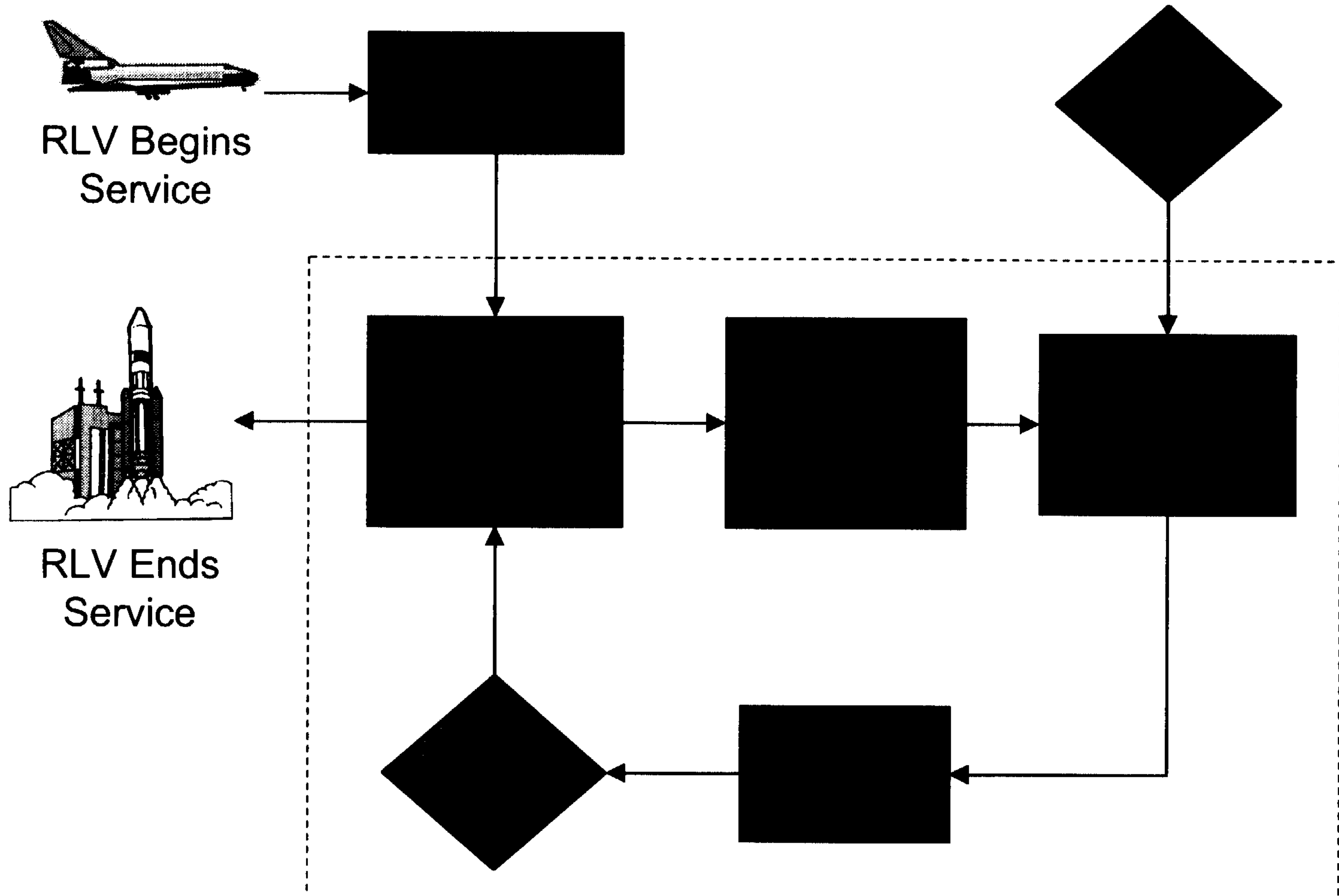
RLV Ground Maintenance



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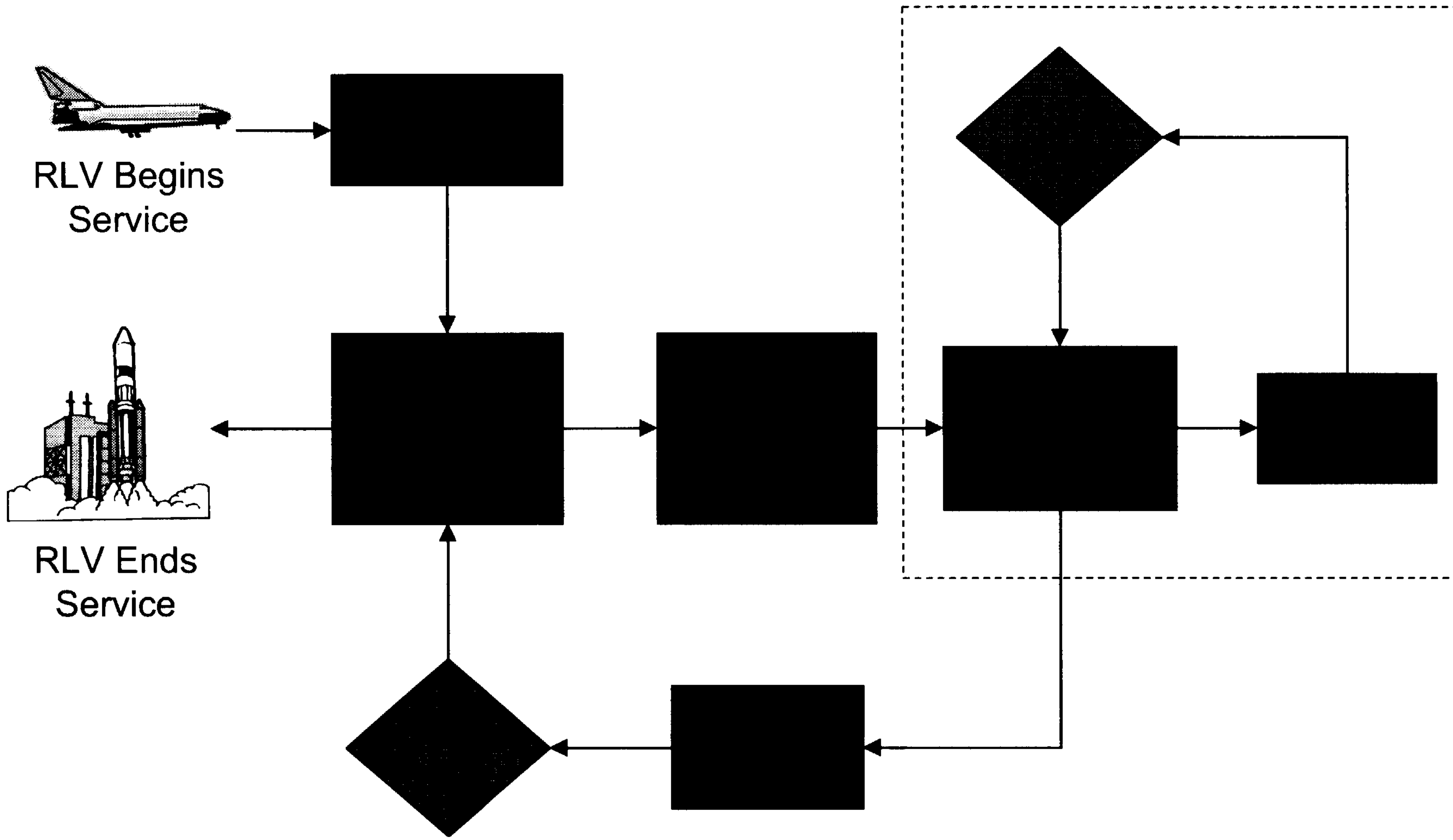
LRU Repair Process

SRU Repair Process



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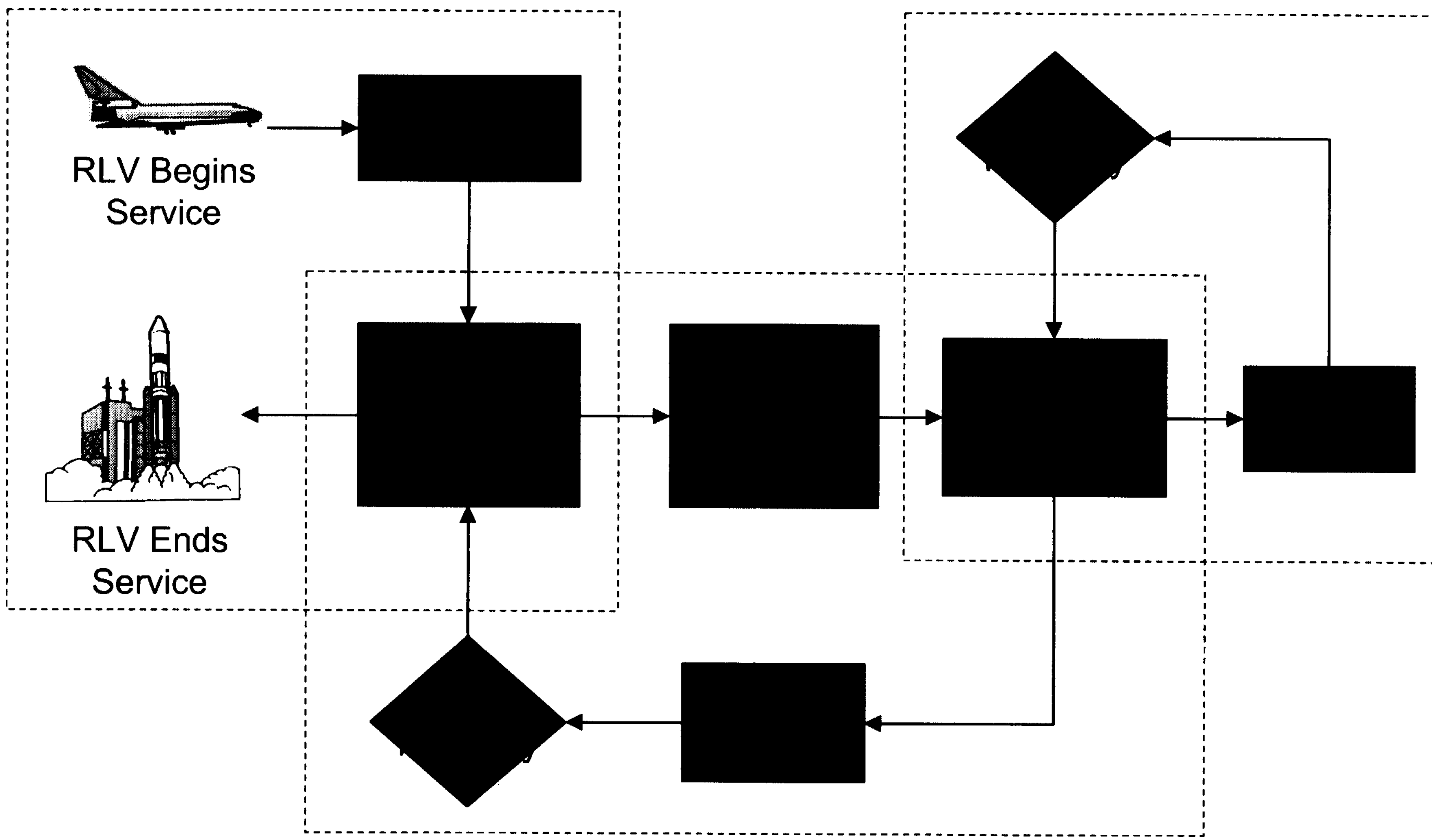

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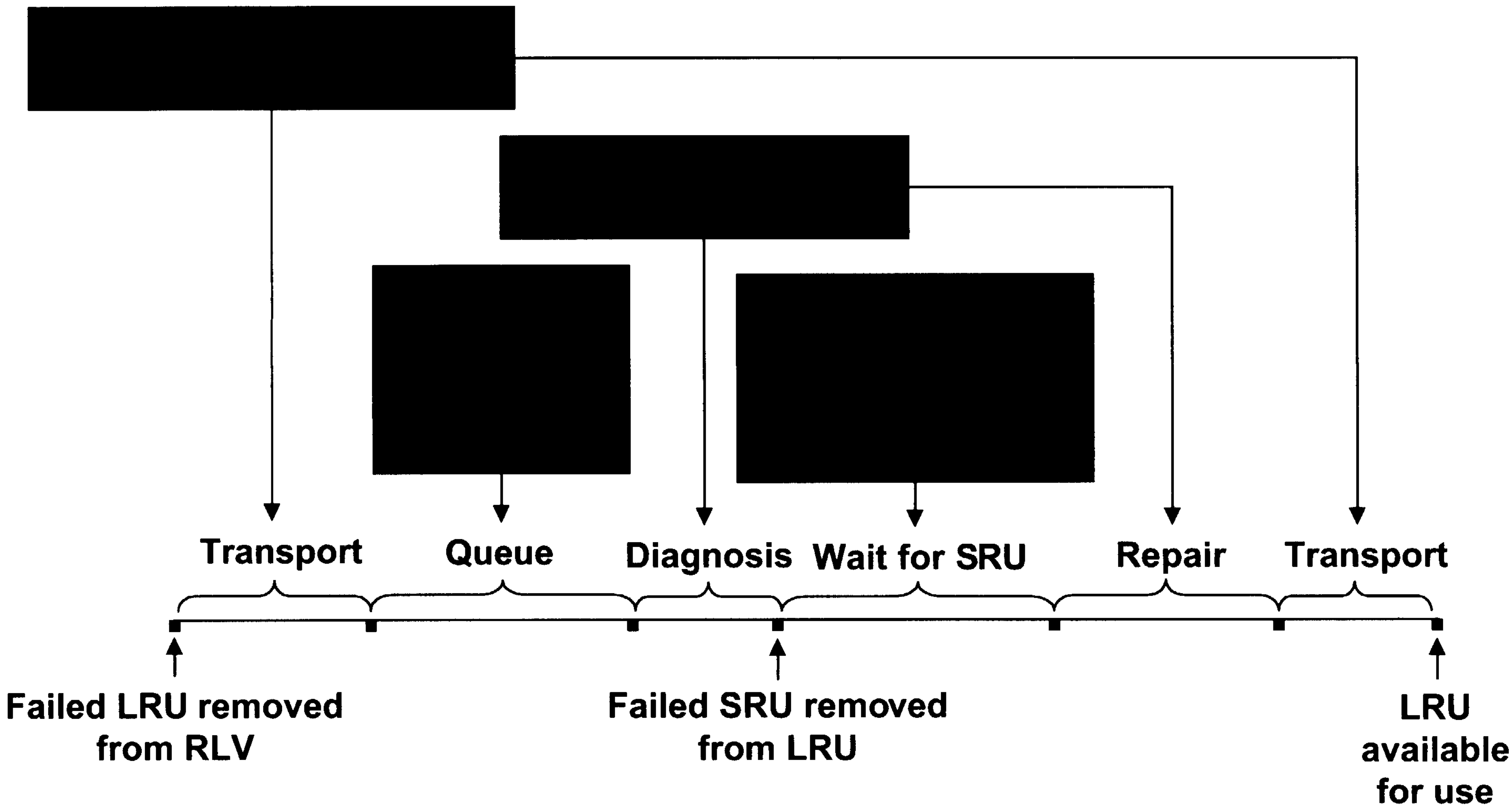
System Framework



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LRU Repair Cycle Time

- System Framework
- Analysis Tools
- Analysis Process (GEM)

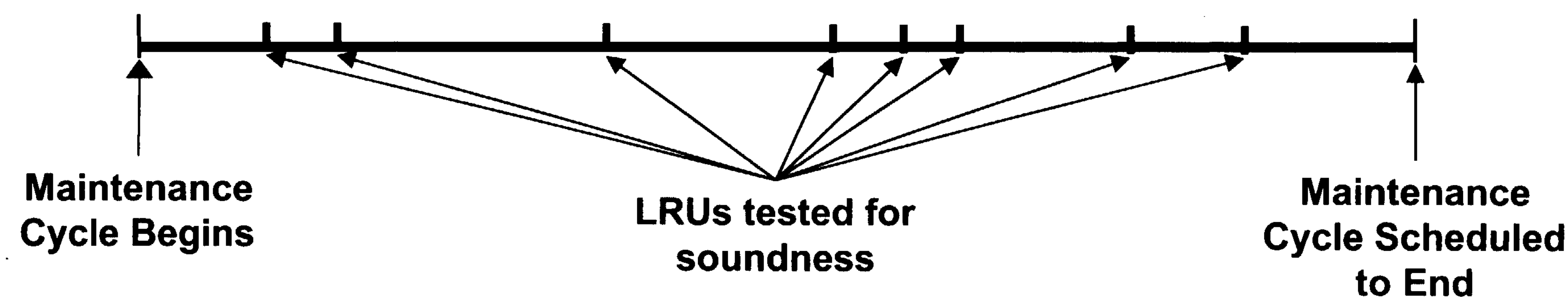
Overview

- Mathematical Model
- Simulation Model

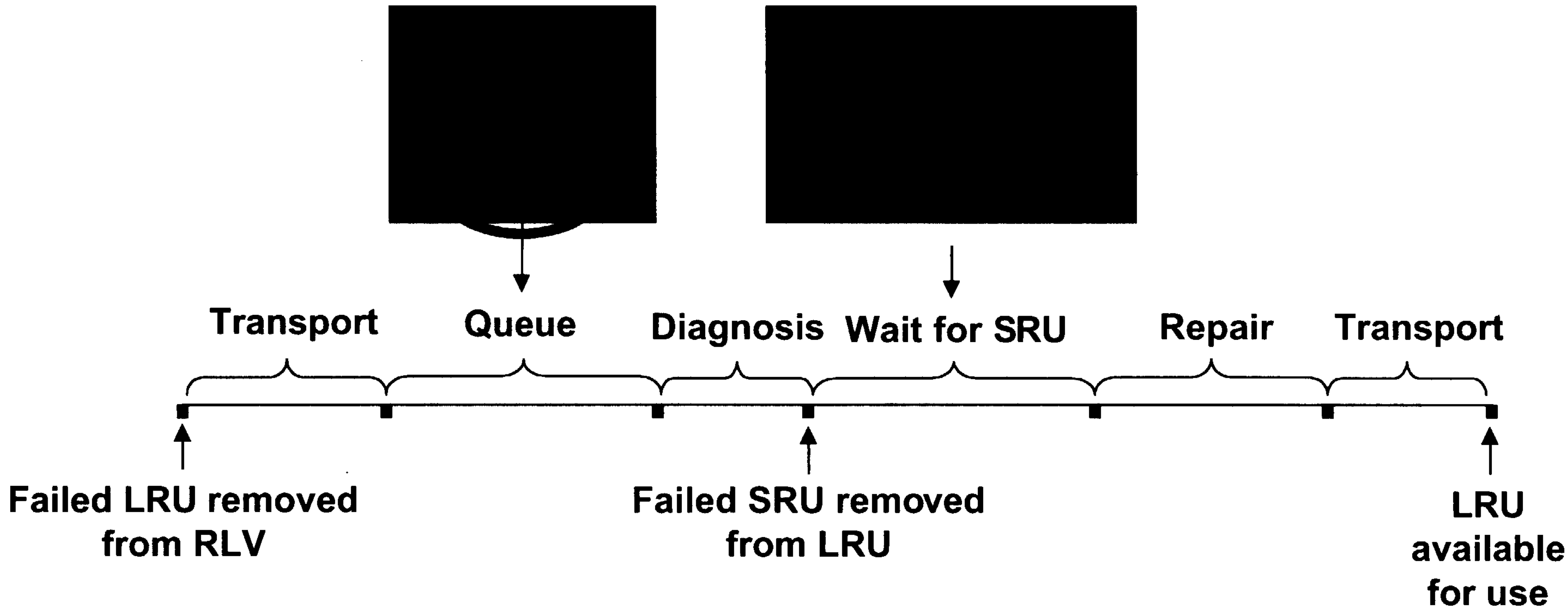
Analysis Tools

Goal:

Given a target investment level, determine LRU and SRU spare inventory levels that minimize the expected number of "holes" in an RLV at the end of its scheduled maintenance cycle.



Mathematical Model



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LRU Repair Cycle Time

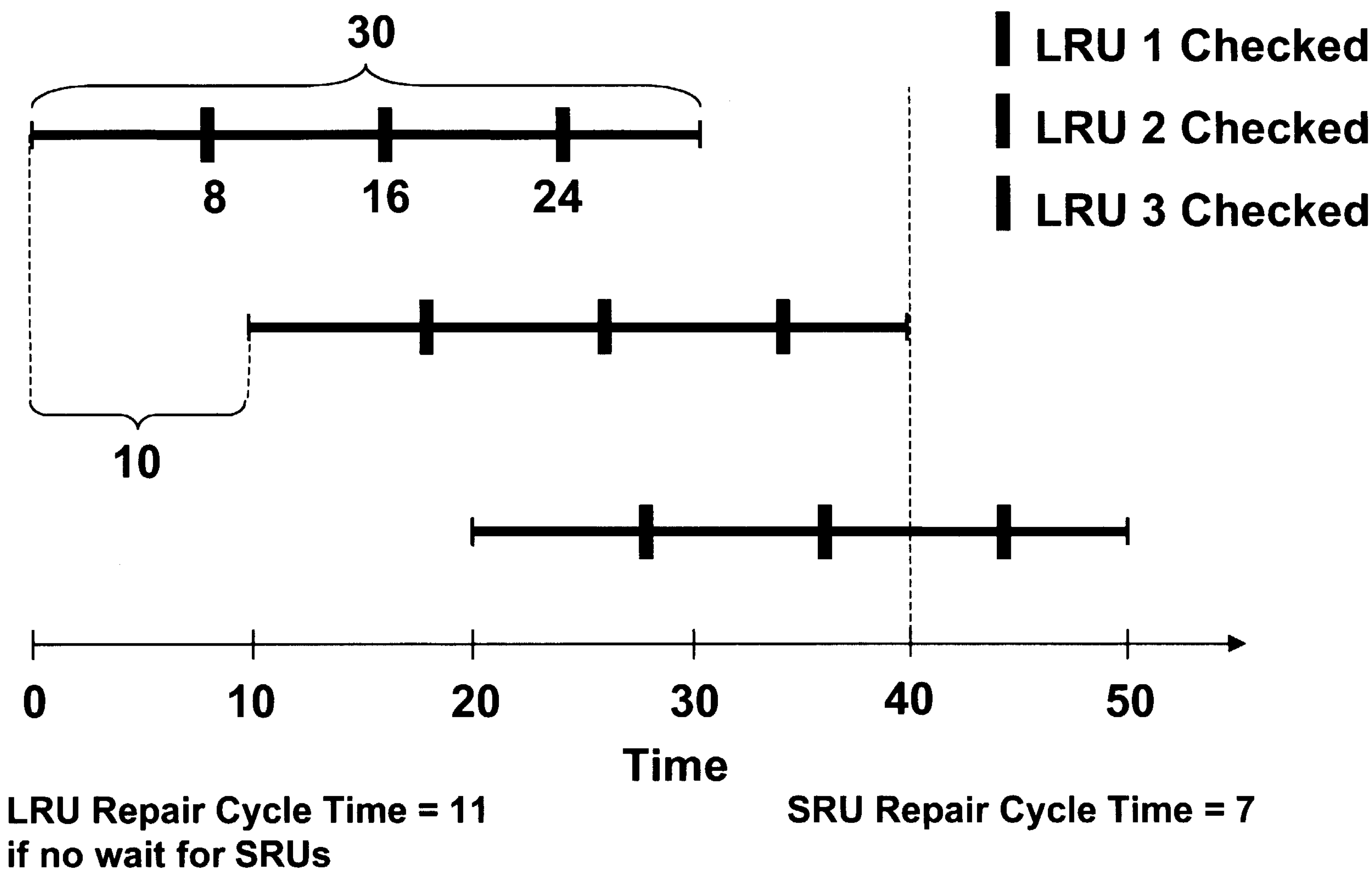
Considerations:

- RLV maintenance schedule parameters (τ, γ, etc.)
- Times at which LRUs are tested (relative to τ)
- Part failure characteristics
- Bill of material relationships
- For LRUs repaired in-house, repair cycle time components (other than queue time and wait time)
- For LRUs with outsourced repair, the repair cycle time distribution
- SRU repair cycle time components (other than queue time)
- Repair capacity
- Target budget level and part costs

Does not capture:

- Variability of transport, queue, and service times
- Work prioritization

Mathematical Model



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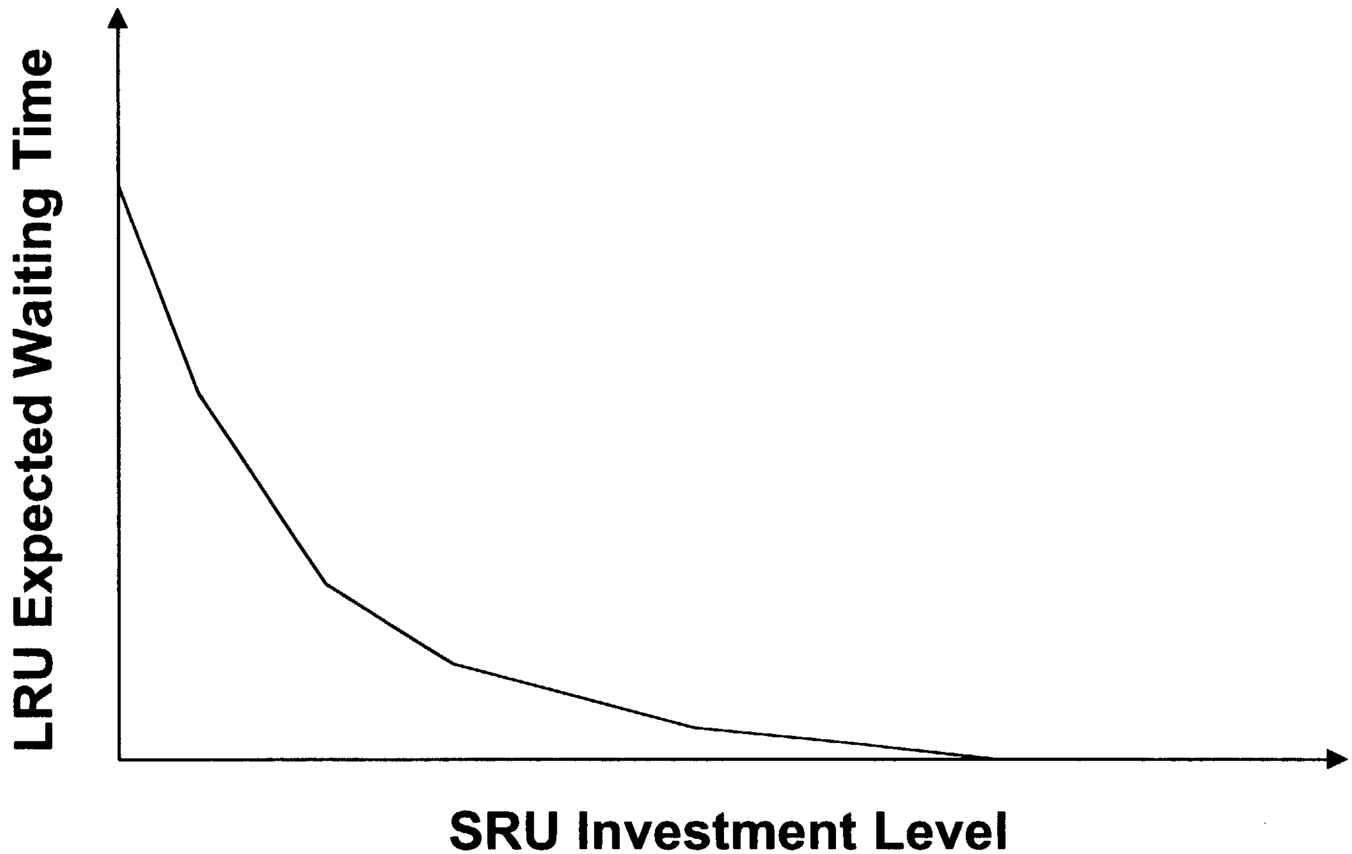
Example

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.



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SRU Tradeoff Curve

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
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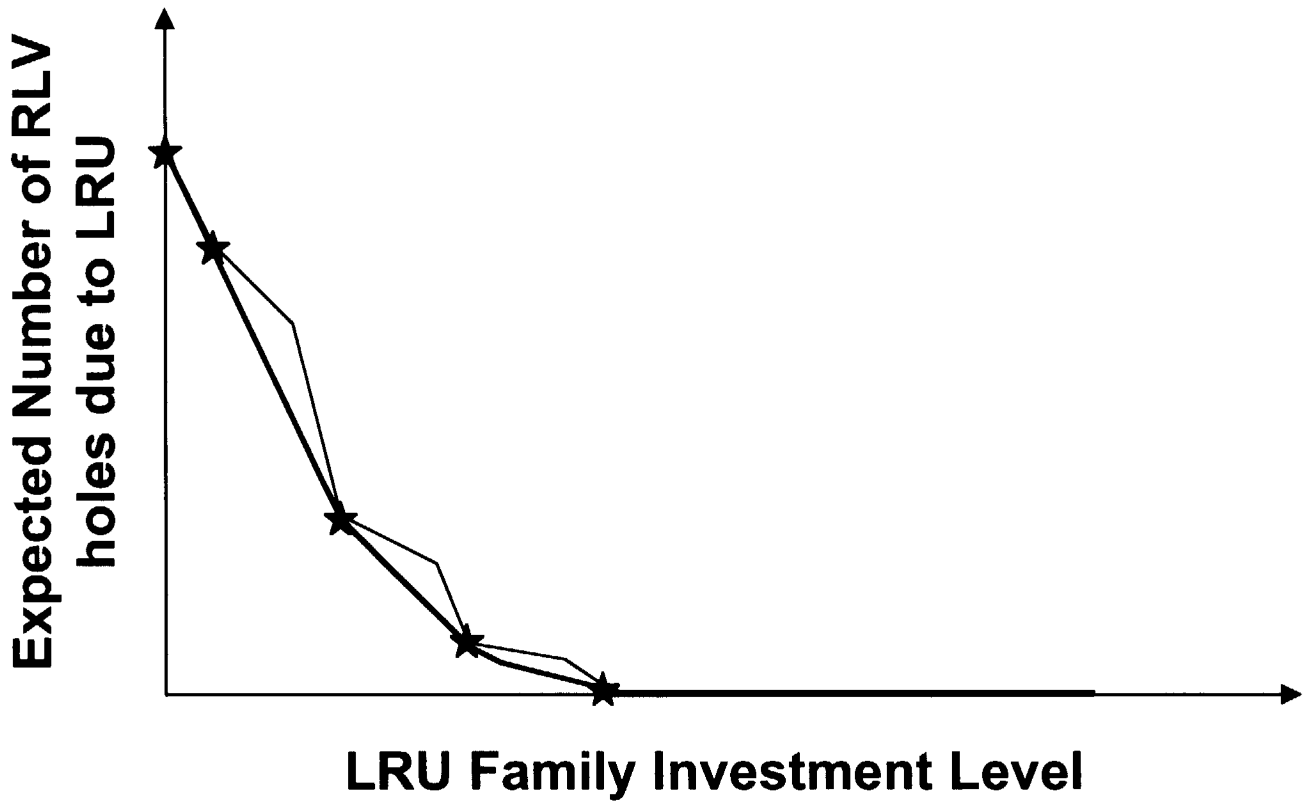

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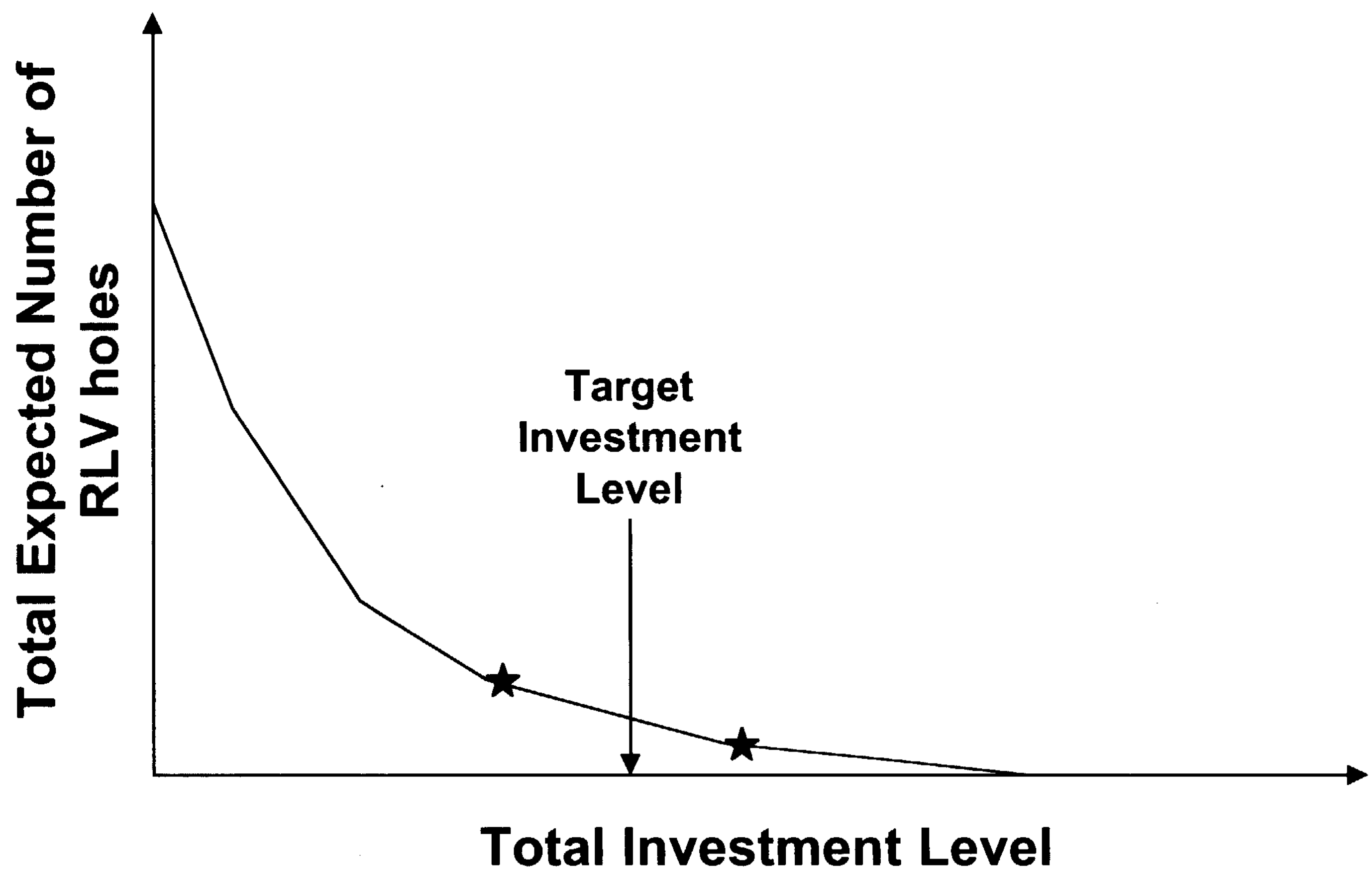
LRU Family Tradeoff Curve

Outline of Method:

- For each LRU type, build the SRU tradeoff curve.
- For each LRU type, build the family tradeoff curve by evaluating LRU/SRU budget allocation strategies, keeping points on the convex minorant of the curve.
- Build the overall tradeoff curve using marginal analysis on the family tradeoff curve points.
- Find the point on the overall tradeoff curve that requires a total investment closest to (but not exceeding) the target investment level.

Determining Spare Levels



Overall Tradeoff Curve

Goal:

Evaluate maintenance resource strategies, including LRU and SRU spare inventory levels, in the dynamic RLV environment.

Considerations:

- Outsourcing of repair
- Condemnation
- Limited capacity for in-house diagnosis and repair
- Probabilistic transport and service times
- Limited inventories
- Dynamic work prioritization at repair centers

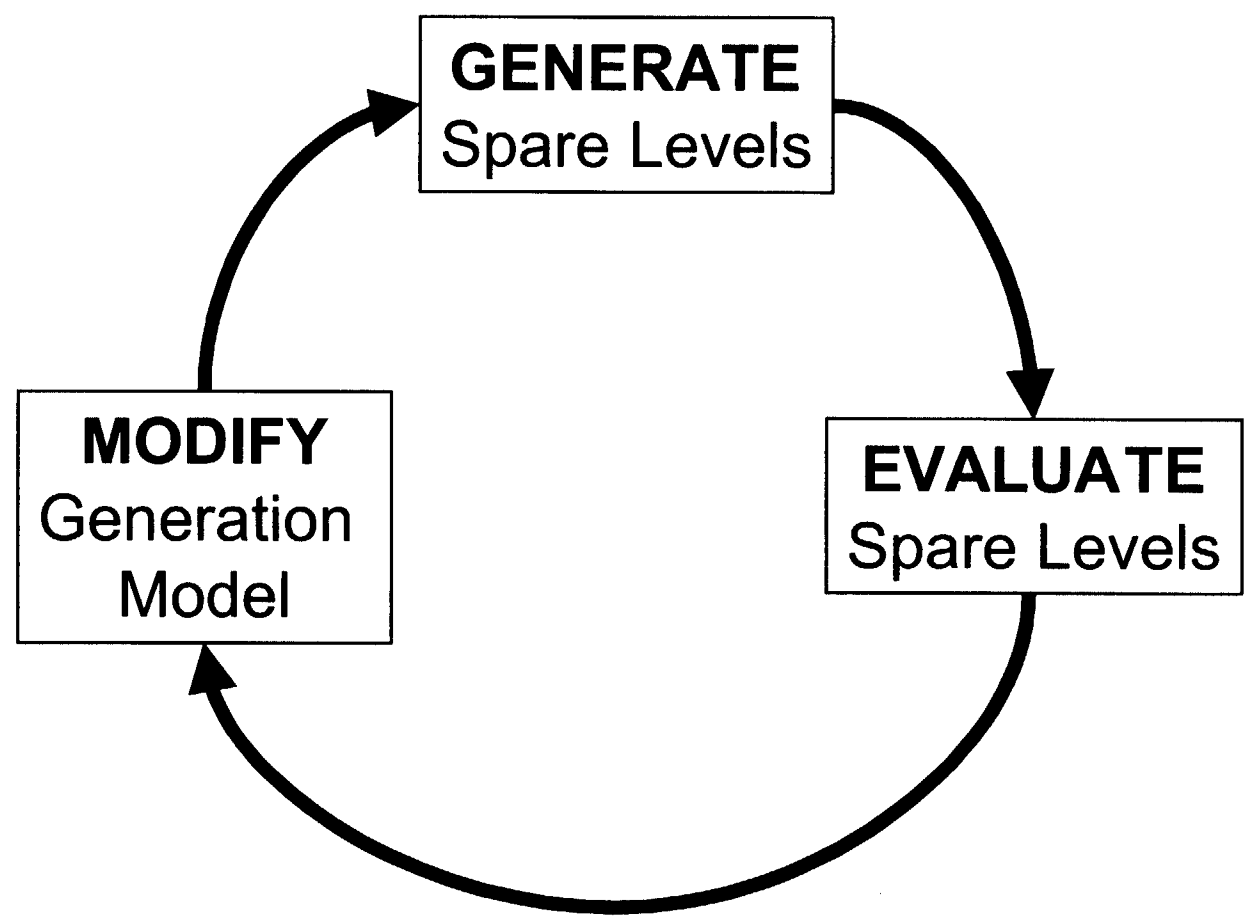
Simulation Model Features

- Identify Events
- Model Delays Between Events
- Manage Priorities
- Track Inventories
- Select Inputs
- Capture Outputs

A Model of RLV Repairs

- System Framework
- Analysis Tools
- Analysis Process (GEM)

Overview



Analysis Process

- Validate models with realistic data
- Use analytic tools to evaluate alternative maintenance resource strategies
- Enhance the current mathematical model
  - Repair queue time variability
  - Repair capacity decisions
  - Repair facility location decisions
  - Repair facility assignment decisions

Next Steps

SFINIX
Scaleable, Fault-tolerant Intelligent Network or X(trans)ducers

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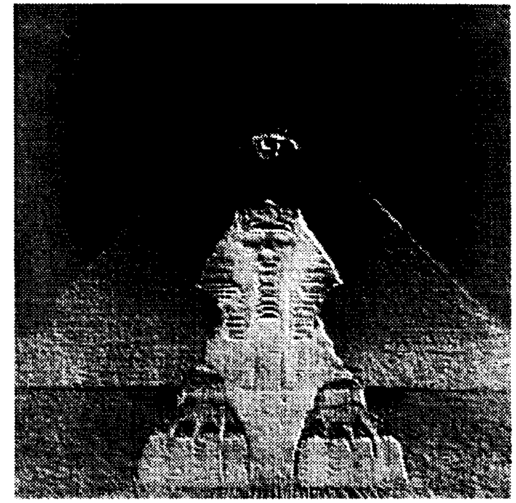
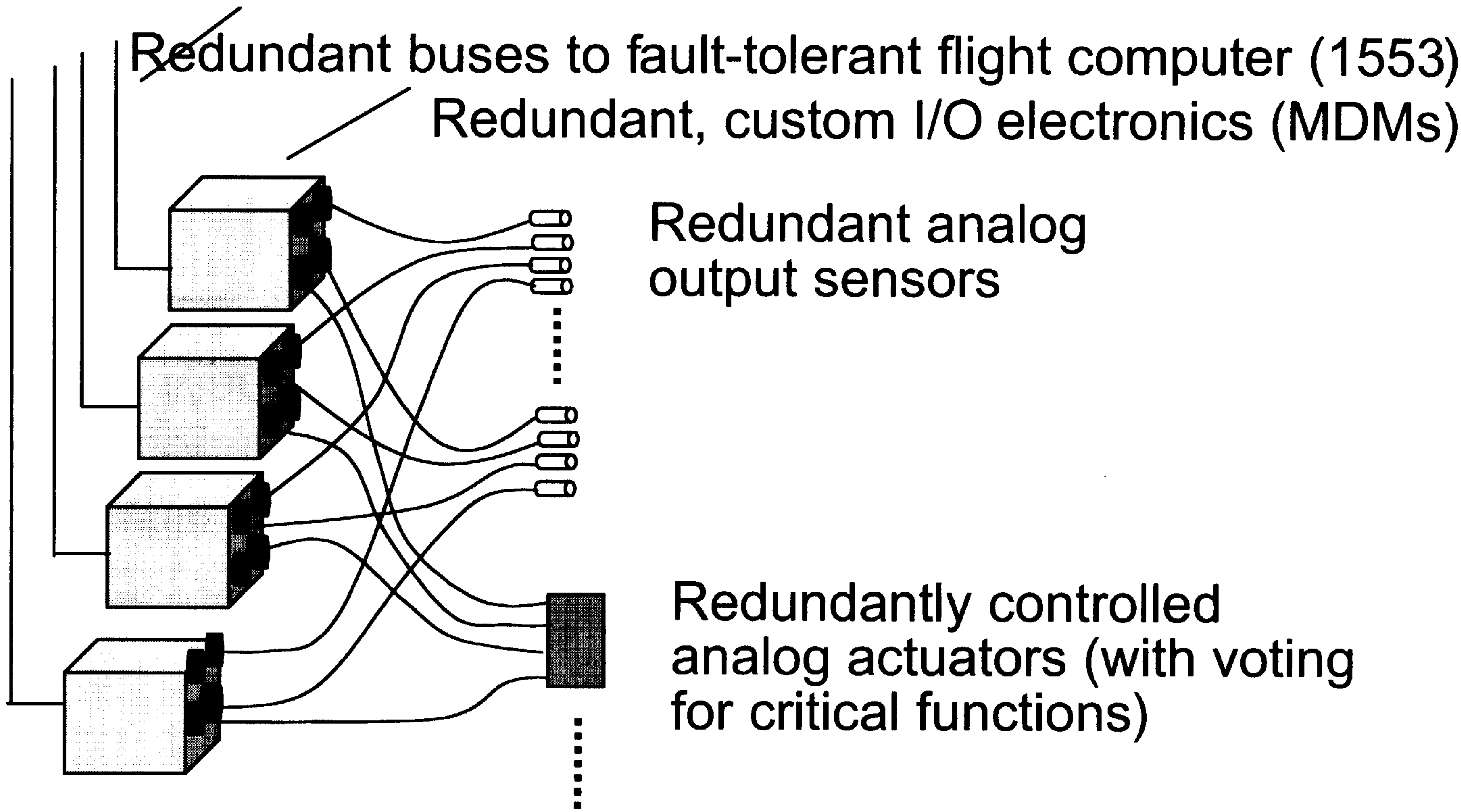
(MSFC/ED12)
256-544-7646
anthony.kelley@msfc.nasa.gov

SFINX

The Intelligent I/O Network
for Future NASA Avionics



Scalable **F**ault-**T**olerant **I**ntelligent **N**etwork of Trans(**X**)ducers
Sponsor: NASA Marshall Space Flight Center (MSFC)
Team Members: MSFC, Draper, Oak Ridge, GP:50
Objective: Develop "smart" sensor technology for spacecraft



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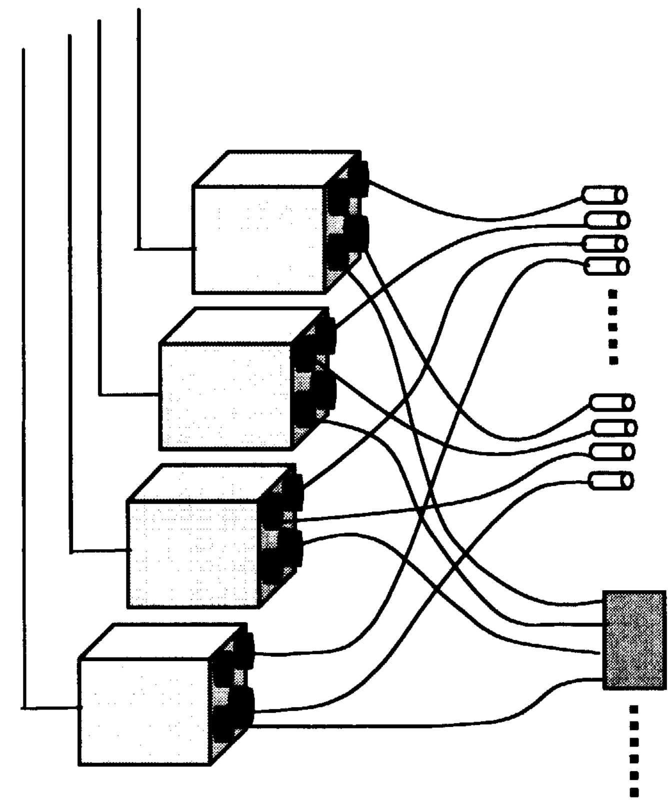
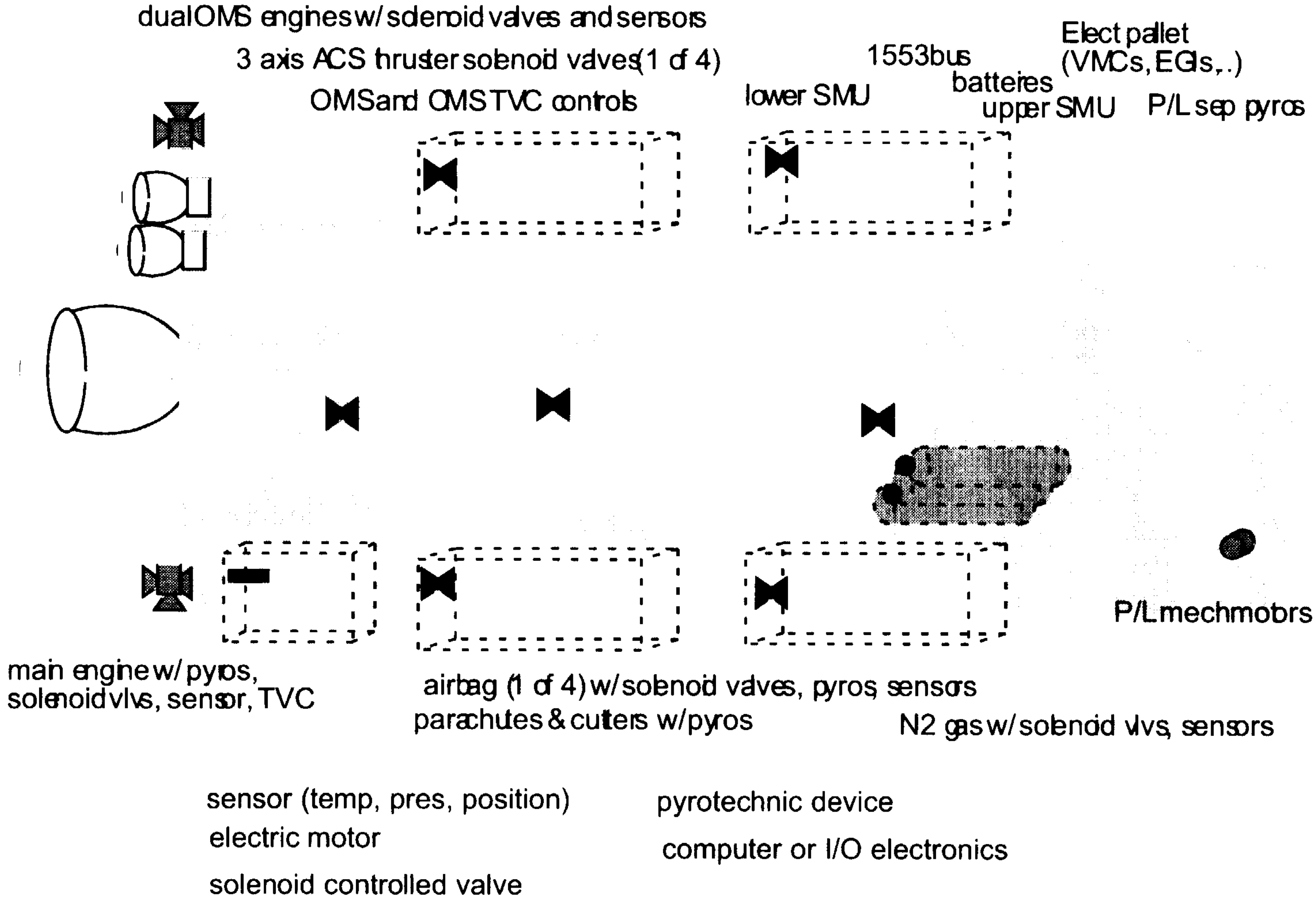
Today's Reusable Spacecraft Utilize Extensive I/O Electronics

- Extensive wiring is expensive to install, reduces reliability
- Growth or change during development is very costly
- Complexity makes checkout difficult, uncertain
- Requires many custom electronic units
- Complex, installation specific software



I/O Installation and Development Discourages Use of Electronically Controlled and Fault-tolerant Functions



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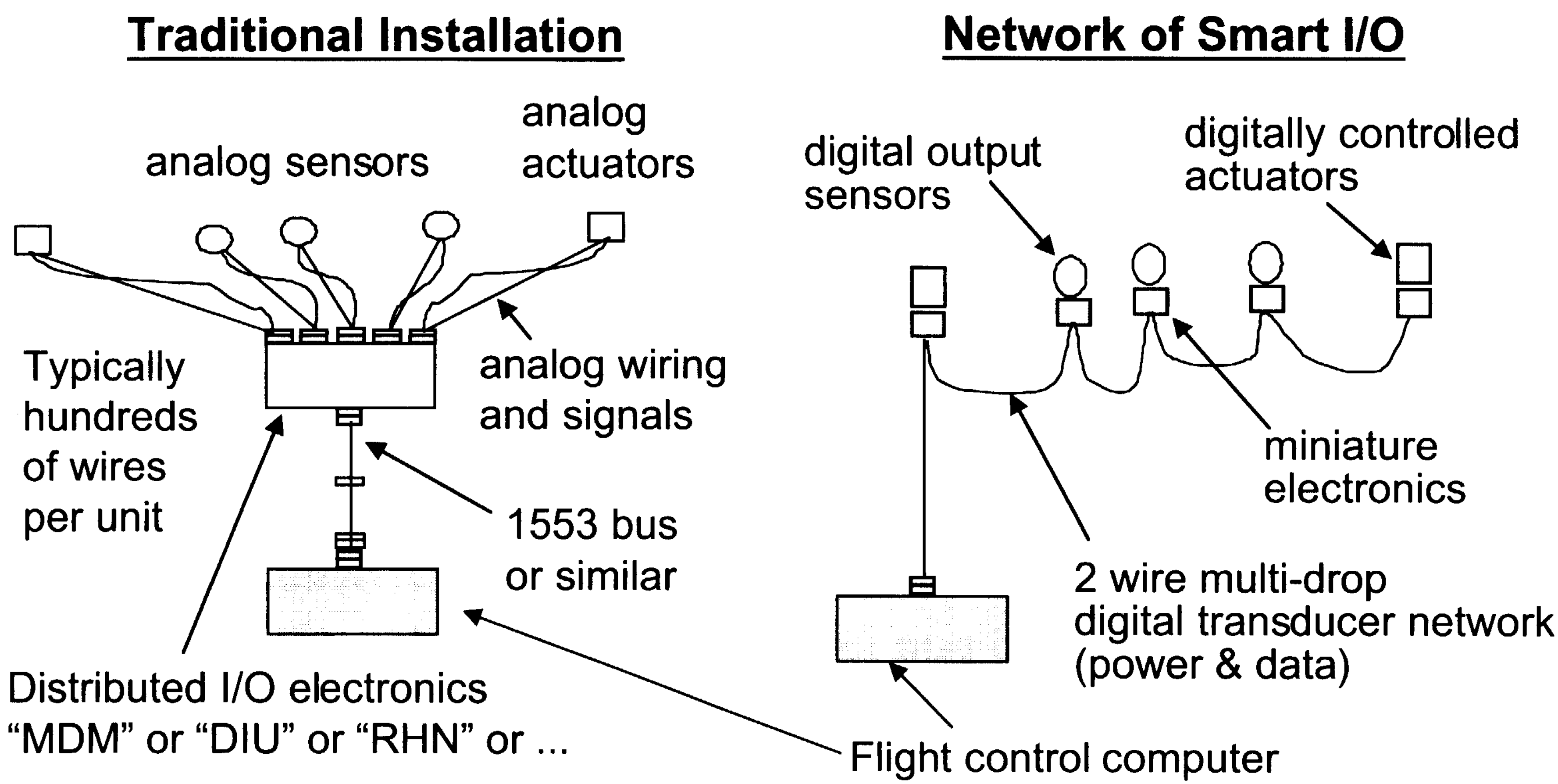
Typical Spacecraft

- **Reduced avionics weight**
  - less wiring and fewer connectors
  - fewer and lighter I/O black boxes
- **Increased automation <u>and</u> dependability**
  - reduce dependence upon flight and ground crews
  - increase use of electronic control and health monitoring
- **Reduce development time and cost**
  - reuse of standard components
  - less application specific software, more "plug and play"
  - installation / upgrade flexibility

Why Use Smart Sensors and Actuators?



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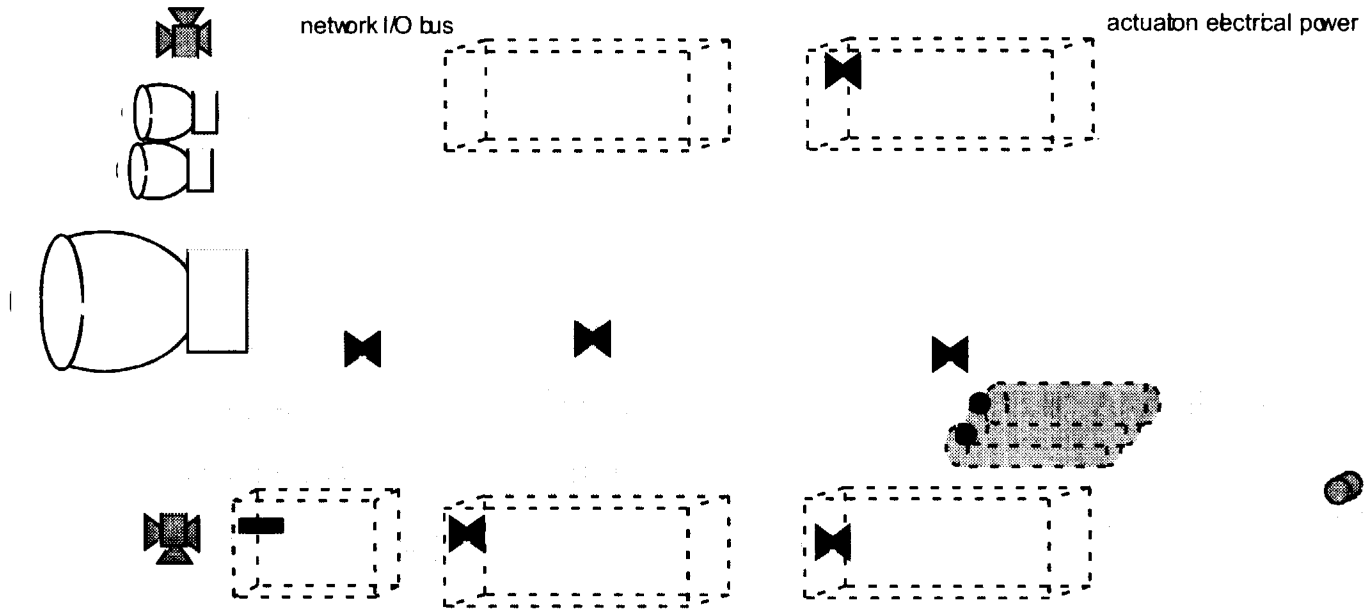
Networks of "Smart" I/O Can Address these Problems



50 - 75% savings in wire weights are possible

smart sensor
electric motor w/ controller
"smart" solenoid controlled valve
pyro w/ companion "smart" driver

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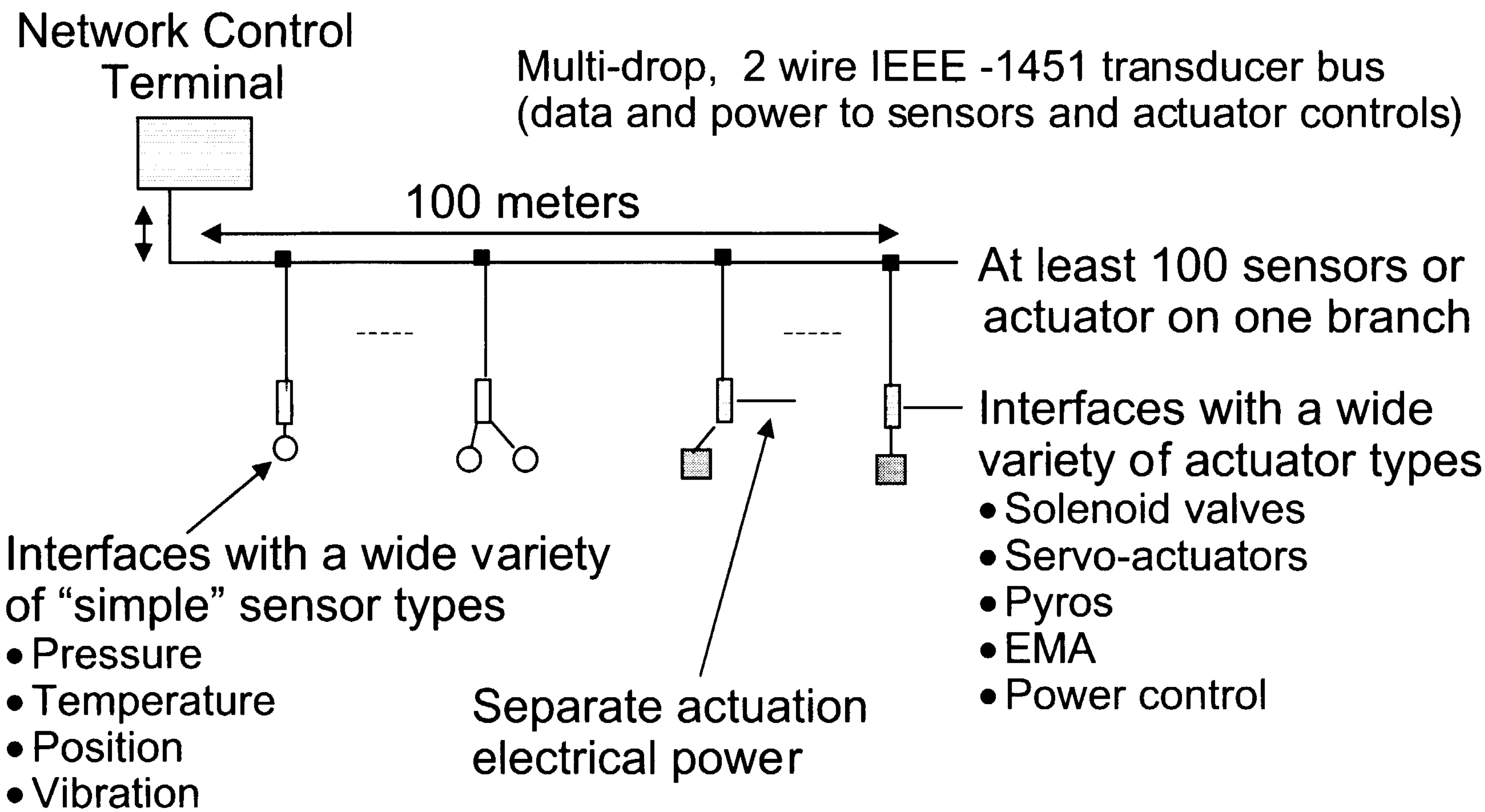
Spacecraft with Multi-drop I/O Network

- “Smart” Network I/O electronics are widely available
  - automotive (CAN bus, J1850,...)
  - industrial control (Fieldbus, Profibus, Lonworks,...)
  - home automation (Intellon, Echelon, Enikia,...)
- The challenge is applying the concept to space applications
  - lightweight, simple to install
  - fault tolerant for life critical functions
  - no repairs during mission
  - severe environments (radiation, temperature, vibration)
  - open, non-proprietary system
  - deterministic command and control

SFINX Challenge - Apply “Smart” I/O Networks to Critical Spacecraft Functions



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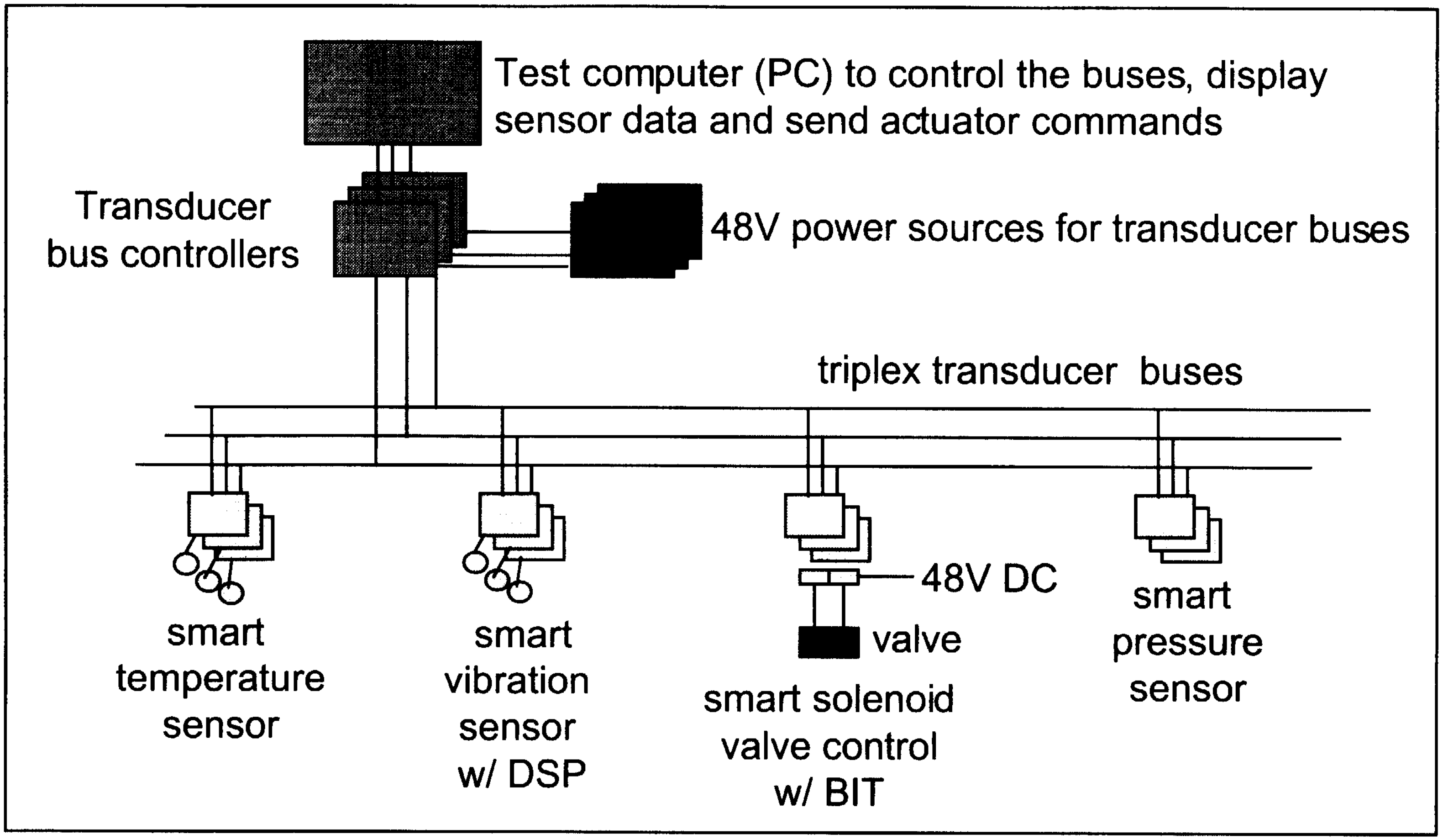
SFINX Requirements - Transducer Network Concept



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SFINX Hardware Demonstration of a Small Scale Sensor / Actuator Network

Future Plans...

- FY01--Demonstrate hardware and software for both RF and 2-wire system
  - Refine 1451 object models
  - Complete 1451.3 standard
  - Analyze distributed real-time architectural impacts and reliabilities
  - Start publishing designs
- Future
  - Append 1451.3 with mixed mode fiber and wire system
  - Utilize ground system based on SFINX
  - Fly SFINX hardware
  - Infuse technology through industry groups

High-Performance Guidance & Control Adaptation for Future RLVs

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"ST Day 2000: Reducing Risk for the Next Generations"

- Motivation for Project
- Technology Goals & Objectives
- Institutional Elements
- Background of Effort
- Current Status & Accomplishments
- Near-Term Plans

Briefing Overview

- Future launch vehicles will continue to have thin performance margins -- through diverse, complex, and demanding missions
  - A rich variety of abort and off-nominal scenari are likely
  - optimality of performance is relevant
- The dynamics of these vehicles will be complicated, e.g. airframe/scramjet interactions, multimode propulsion, etc.
  - Calculation of efficient (optimal) controls not straightforward
  - Certainly not straightforward for reliable online adaptation to new scenari!
  - Complicated dynamics lead to additional uncertainty in modelling, which must be addressed to preserve performance (alternative is robustness, which costs performance)

Motivation (1)

- "Airline-like" commercial operation infeasible without automation of guidance & control design/abort/contingency planning functions…
  - "Airline-like" model is rendered difficult by thin performance margins, higher energy levels, and lack of a pilot for responding to unplanned situations.
  - Onboard "optimal" adaptation needed to prevent a combinatorial explosion of preplanned cases!
- This technology is certainly not "state of the art," and does not exist for complicated nonlinear scenari associated with hardware failures and aborts
  - The technology must be developed, and we hope that this project is successful in doing so.

Motivation (2)

- **Develop theory and computational techniques for:**
  - **high-performance (I.e. optimal) inner/outer loop control which reliably**
    - accommodates and exploits propulsion/airframe interactions
    - changes, for changes in vehicle health or mission
    - provides timely revision of mission profile for abort scenari
    - formally addresses uncertainty in the system
  - **Validate new technology in appropriate experimental environments, as it matures…**

"Baby" simulations

Vehicle simulations

MAST

"Generic" test fixtures

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Technology Goals & Objectives

- **People:**
  - **LaRC (0.5-0.75 FTE)**
    - guidance, nonlinear control, preliminary sim development
  - **MSFC (0.5 FTE)**
    - navigation, control, MAST coordination
  - **GRC (1.5 FTE)**
    - control of airframe/propulsion interactions
- **Validation Assets:**
  - **Simulink adaptation of 6DOF "Marshall Aerospace VEhicle Representation In C" (MAVERIC) -LaRC/MSFC**
  - **Flying Flexible Fixture (FFF) - LaRC**
  - **Marshall Avionics System Testbed (MAST), INS/GPS Lab - MSFC**

Institutional Structure of Effort

- **This work extends from GN&C technology developed under Bantam...**
  - **Neighboring Optimal Control (NOC) techniques for systems with constraints**
    - provides reliably available near-optimal performance “near” known missions
  - **uncertainty modelling techniques for μ synthesis and analysis**
    - permit formal balancing of robustness against performance for linear feedback systems
  - **development of “Flying Flexible Fixture” (FFF)**
    - low-cost laboratory scale “difficult, highly nonlinear, unstable” flying system for evaluating nonlinear control concepts
  - **preliminary development of INS/GPS lab at MSFC**
    - permits inclusion of INS/GPS navigation issues in MAST simulations
    - permits high-fidelity evaluation of navigation filter concepts

Background of Effort

- NOC technique being refined…
  - current mix of Matlab and FORTRAN90 software shifting entirely to the latter
  - revision of temporal discretization to satisfy POO principle of optimal control
  - inner/outer-loop numerical optimization technique for improvement of optimal trajectory convergence currently under Monte Carlo testing

- Matlab toolbox under development to combine μ uncertainty modelling computational algorithms (this work leveraged against NASA Aviation Safety Program effort)

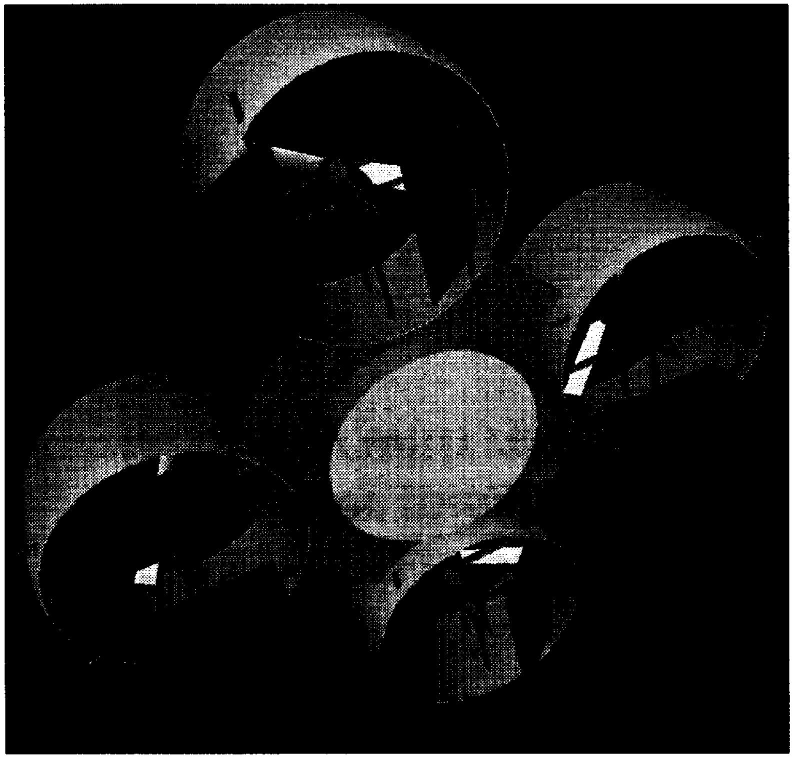
- LaRC & GRC settling on joint dynamical model or family for hypersonic airbreather

Current Status (1)

- MSFC starting an extension of INS/GPS evaluation and development lab to interface with MAST for realistic nav-in-loop technology evaluation.

- LaRC developing Simulink adaptation of 6DOF Maveric for joint LaRC/MSFC/GRC simulation studies.

Current Status (2)

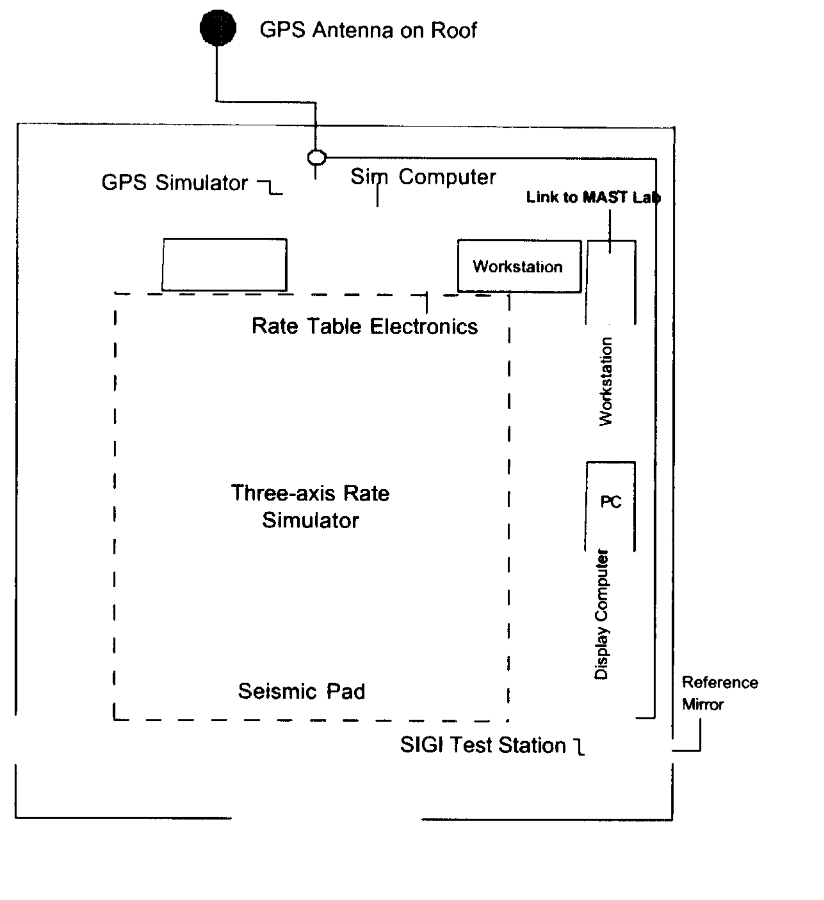


- Electrically powered
- 28 lbm, 40 lbf max thrust
- 12 DOF control
- controlled via radio link to dSpace control system that hosts simulink-based user concepts.

- Aero testing in progress for powered flight
- System certified for safe operation

Flying Flexible Fixture Status

- Develop and test GN&C blending filters
- Robust filter design to allow for a variety of inertial measurement units and Global Positioning System (GPS) receivers used in different trajectories
- Develop MSFC expertise in blending filters design for greater mission flexibility with reduced cost



Robust GN&C Evaluation Lab

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Robust Navigation and Guidance

- **FY01**
  - **(4Q) Complete hardware integration of INS/GPS evaluation and development lab.**
    - Output: lab will be available for developing open-loop sims of INS/GPS systems and tools will be in place for development of easily-configurable kalman filters providing blended INS/GPS nav solutions
  - **(4Q) Develop generic 6DOF Simulink sim, congruent with MAVERIC, suitable for G&C studies, populated with parameters for a relevant vehicle**
    - Output: sim will be available for rapid prototyping of guidance and control architectures, and their simulation-based evaluation. Elements of vehicle dynamics will be easily visible and available for modification and analysis.
- **FY02**
  - **(4Q) Develop nonlinear probabilistic/uncertainty model structure for RLVs. Populate with parameters for vehicle under study.**
    - Output: vehicle model will be extended to provide probability distributions of quantities related to dynamical response behavior.

Near-Term Milestones

Evolvable Hardware for 3rd Generation Avionics

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A collaboration between JPL and NASA ARC

JPL EHW page: http://cism.jpl.nasa.gov/ehw/darpa/

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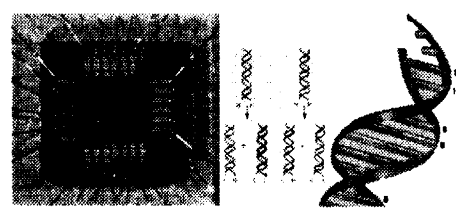
- We propose to develop “evolvable” circuits that would self-reconfigure under the control of biologically inspired genetic and evolutionary algorithms and would be directly implemented/integrated with the hardware itself.

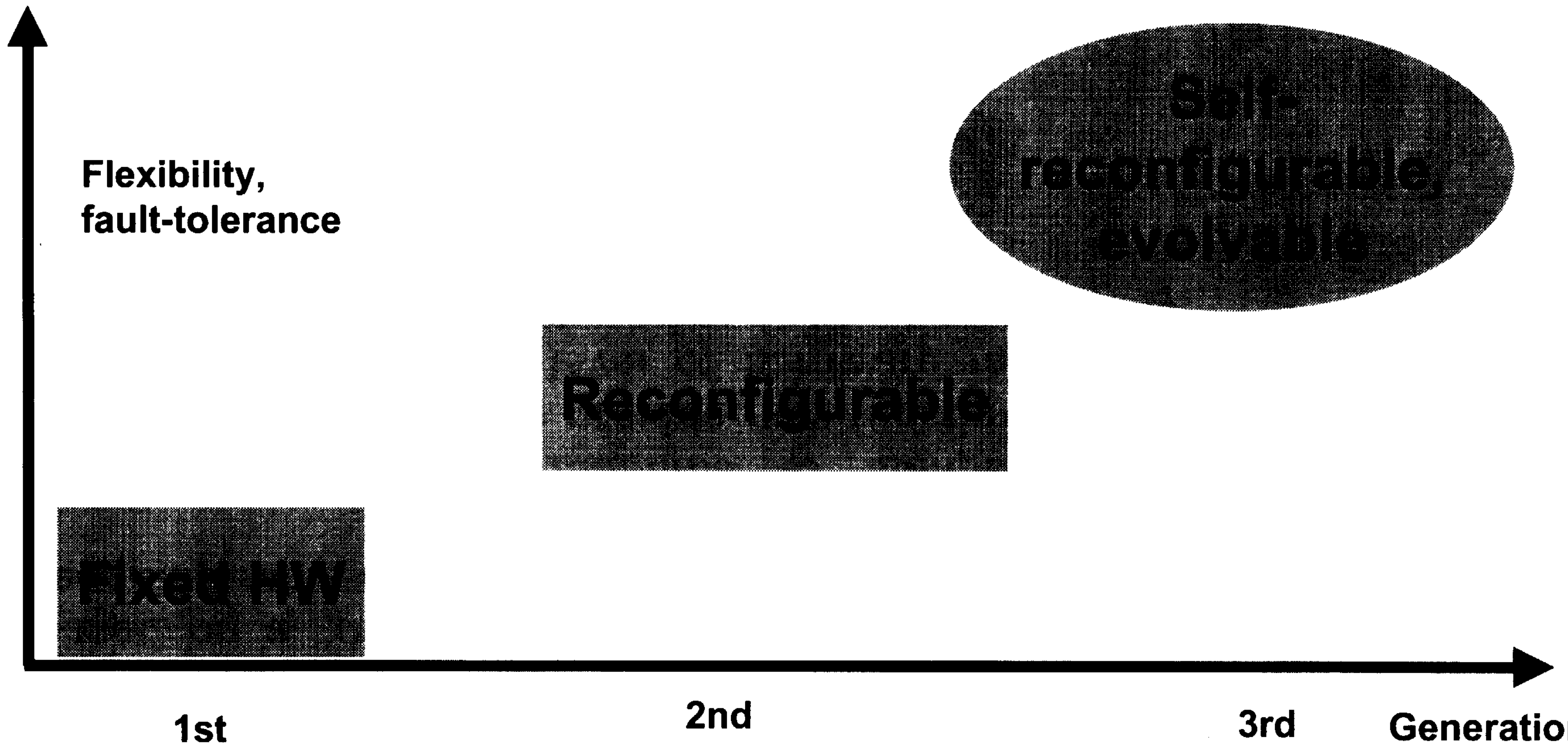
- The objective is to demonstrate by 2006 a flight system prototype based on a “diehard” architecture, seamlessly integrating functional reconfigurable circuits and evolution/self-configuration mechanisms.

- Circuits evolving in real-time to compensate for unanticipated faults/damage and/or to provide new functionality on-demand, without the conventional high level of hardware redundancy would provide light-weight and low-cost avionics with high reliability.



Technology Goals and Objectives

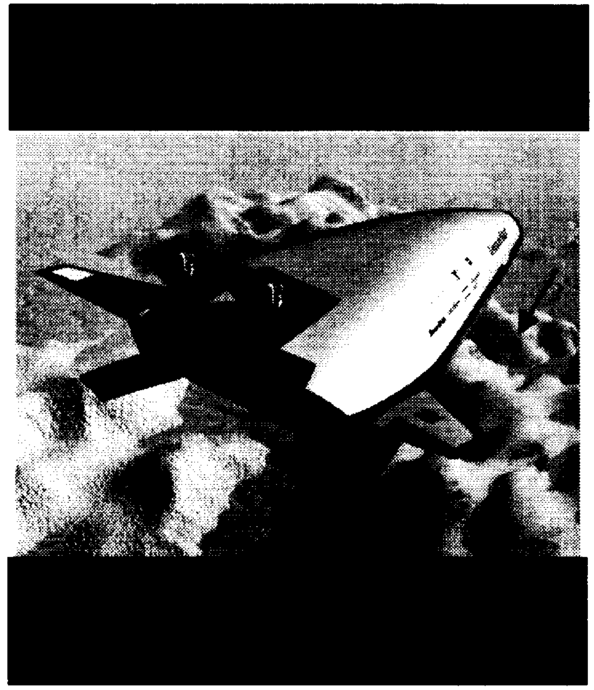
Generation change: fixed hardware, reconfigurable hardware, evolvable hardware



"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Technology Goals: 3rd Gen. Avionics

Survivability:
Maintain functionality through parametric adjustments even with changes in hardware characteristics (e.g. due to radiation, temperature, aging and malfunctions)



Versatility/Flexibility:
Create new functionality through synthesis of totally new circuits for new missions, dramatic changes in requirements or environment

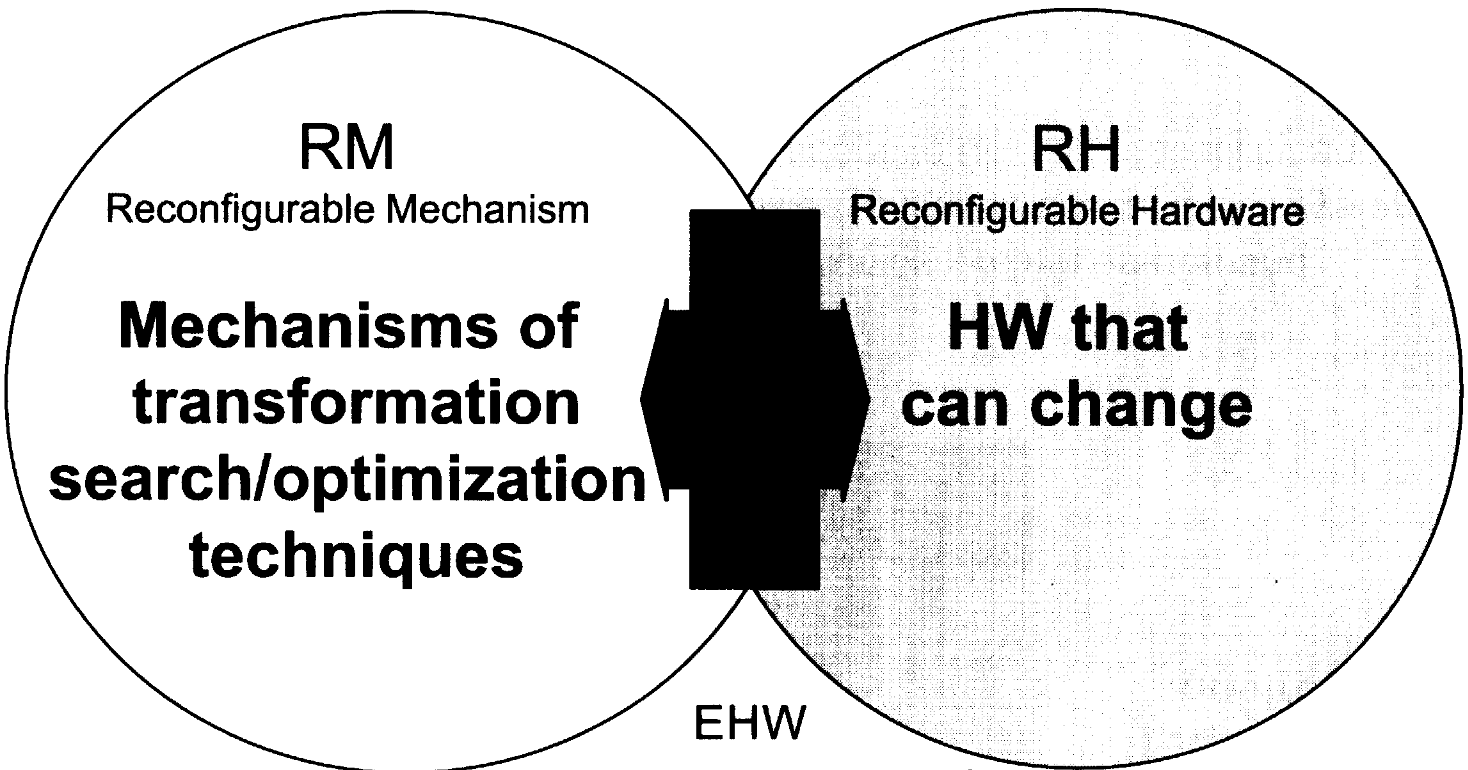
♦ Benefits

- Enable new and multiple functionality of avionics system on-demand.
- Self-monitoring and self-healing capabilities in time-critical avionics system.
- Enable lightweight, low-cost avionics for adaptive ultrahigh reliability and autonomous GN&C

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Background: Motivation

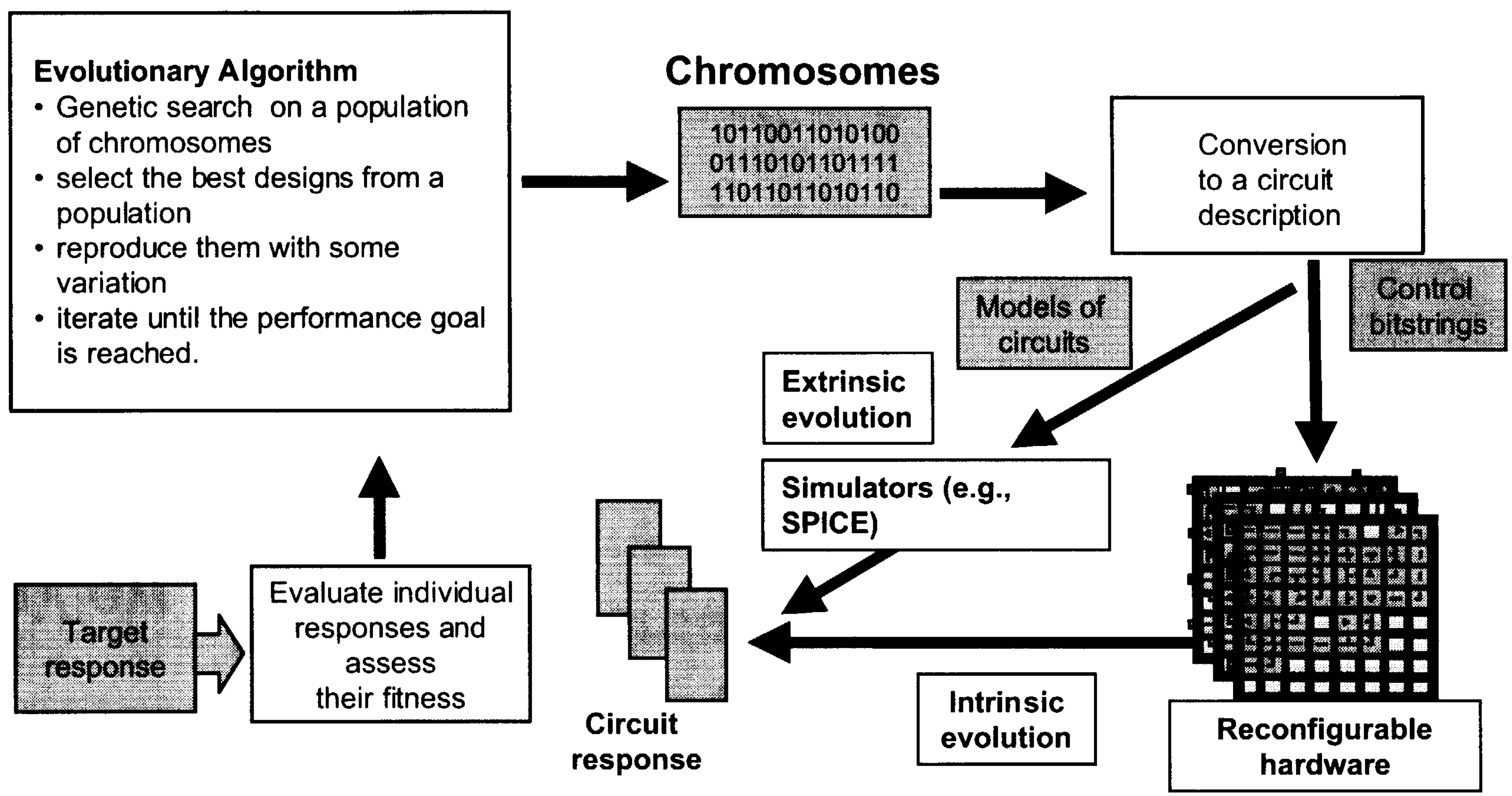
Evolvable Hardware = Reconfigurable Mechanism + Reconfigurable Hardware



Current research in EHW focuses on reconfigurable hardware that self-configures for optimal functionality under the control of evolutionary algorithms.

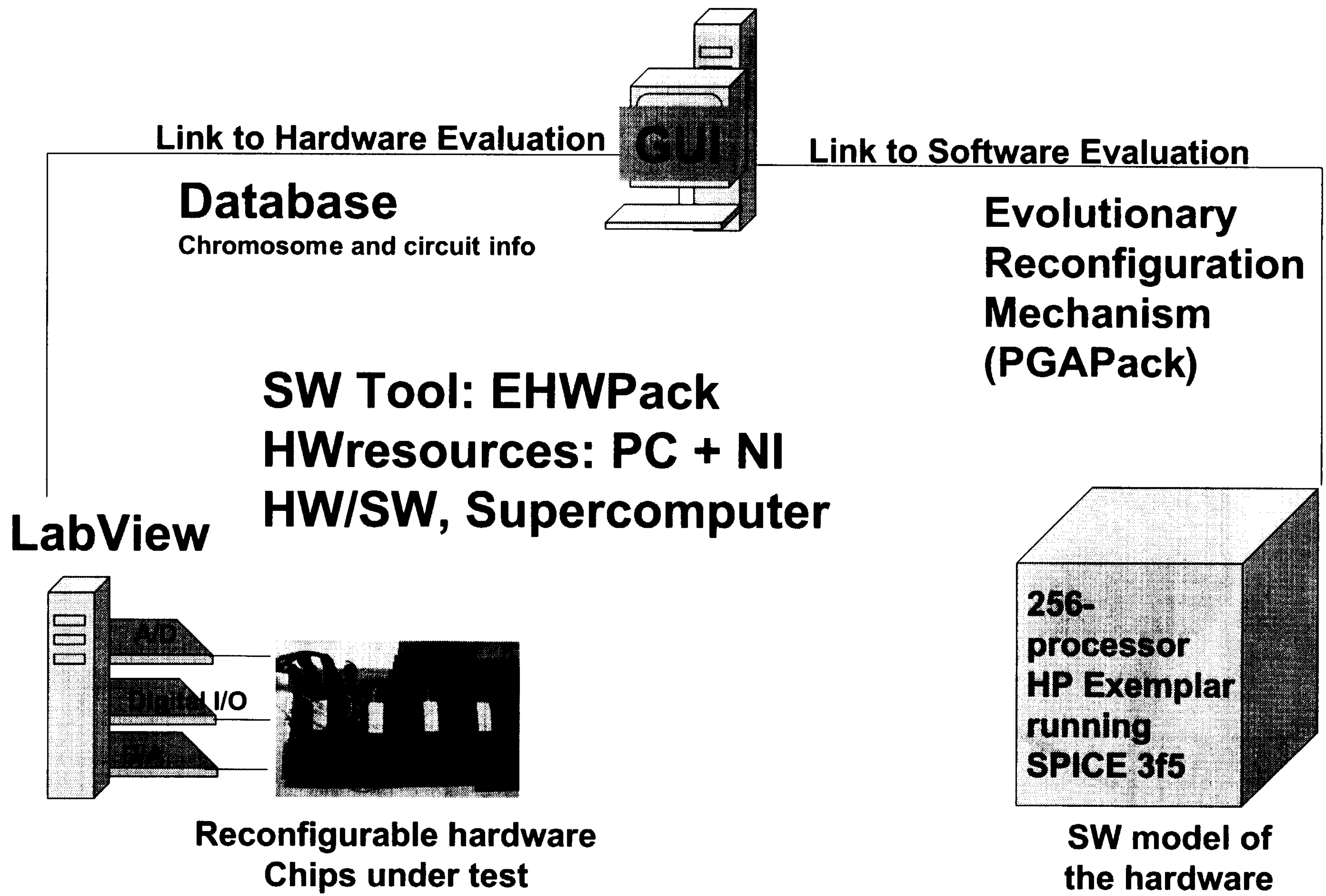
Background: Evolvable Hardware

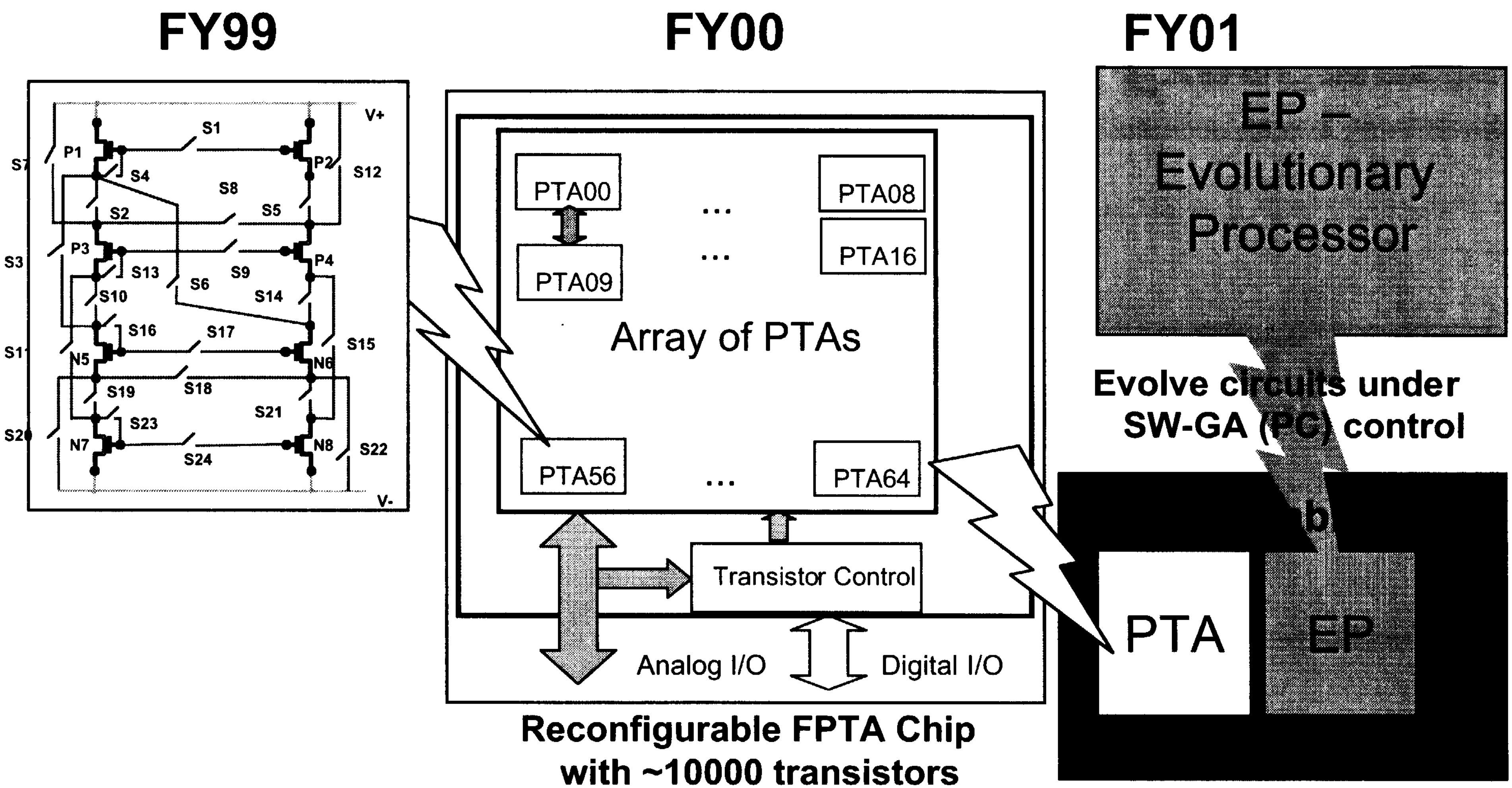
Current Status: Evolutionary synthesis and adaptation of electronic circuits



Potential electronic designs/implementations compete; the best ones are modified to search for increasingly more suitable solutions

Current Status: Testbed





Evolvable Hardware System - Roadmap
From Component to Array on a Chip to System Board

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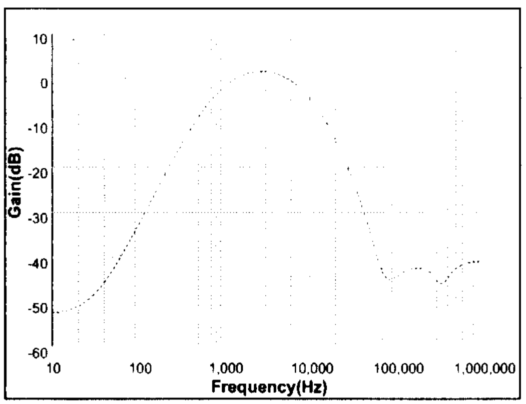
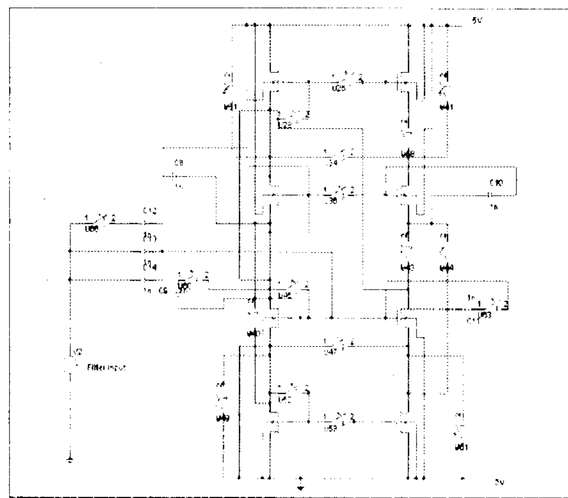
Current Status:
DARPA-funded hardware development

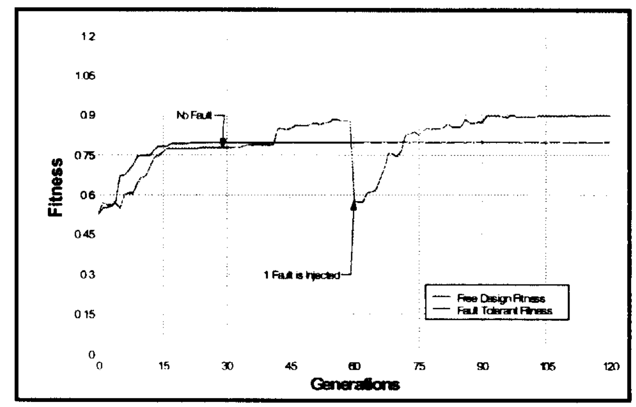
Major Accomplishments: EHW Experiments

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

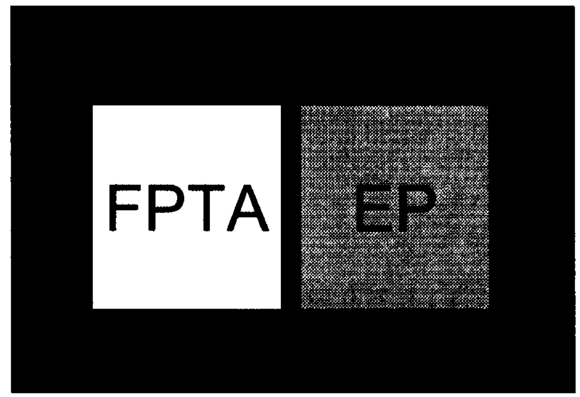
- **Evolutionary circuit synthesis and repair**
  - **Synthesis**
    - Analog computational circuits (fuzzy neuron, multipliers)
    - Logic Circuits (XNOR, AND gates)
    - Filters (band-pass)
  - **Repair: From faults and degradation with temperature**





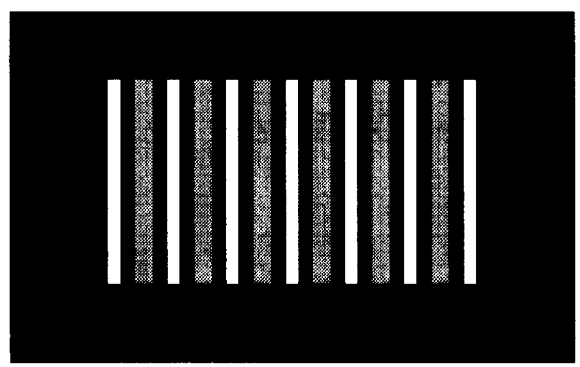


- Demonstration of EHW on a PCI card
  - Two chips, one for Field Programmable Transistor Array and one for Evolutionary Processor



- Development and Simulation or a “diehard“ architecture

Seamlessly integrated “Diehard” architecture



Near term plans :FY01

Phase 1: Conceptual development of a “die-hard” architecture, i.e. a way of distributing the adaptation/self-configuration mechanism into the reconfigurable hardware.

Phase 2: Design and building of evolution-oriented chips and testing them in the context of selected, relevant applications. The tests would include synthesizing new electronic functions, recovery from faults, radiation and temperature hardening.

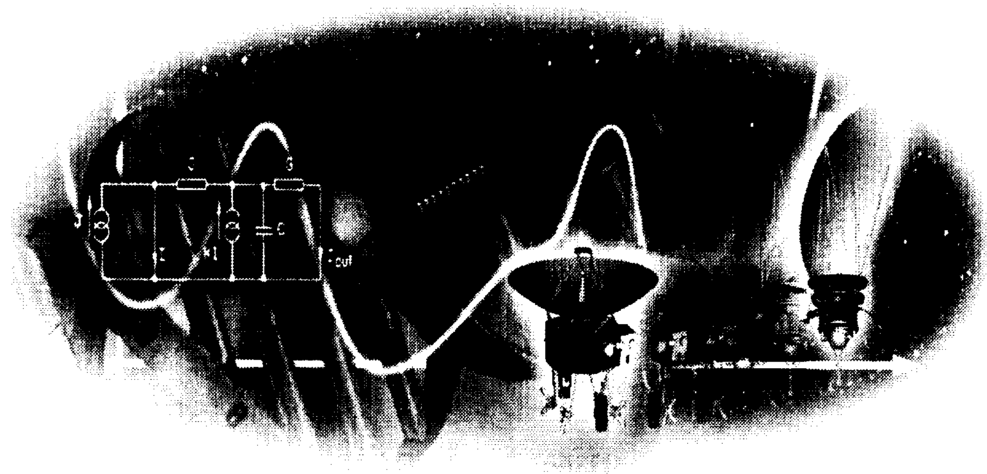
Phase 3: EHW would be integrated with a selected set of sensors within the framework of an on-board avionics computer.

Phase 4: Preparation of flight test.

Plans

- Risks
  - Evolution time is currently around minutes. It must be reduced to a few seconds, otherwise only non-time-critical applications may be impacted.
  - Scalability of the evolutionary approach to complex electronics systems still needs to be proven.
  - Currently, the implementation of the adaptation mechanism must be flawless.
  - If it can not be made fault-tolerant, the mechanism must be isolated in a protected area.
- The EHW technology has the potential to:
  - Enable multiple functionality of avionics systems using the existing resources that are reconfigured as needed.
  - Adapt and self-configure the avionics to new needed functionality
  - Self-heal and be fault-tolerant by rerouting around completely damaged components and reusing components with modified/altered characteristics in new circuit topologies.
  - Autonomous self-configuration.

Risks, Pay-off



EHW technology has the potential to be the underlying technology behind the avionics infrastructure (not only the electronics but also smart optical/structural/thermal subsystems through reconfigurable/morphing/adaptive MEMS/ materials) of the space systems for 2020 and beyond.

Advanced Electric Actuation Devices and Subsystem Technology

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- **Goal:**
  - Develop two high horsepower (>80Hp)redundant EA Subsystems using advanced motor and power electronics designs, control techniques and lightweight structures. Demonstrate at a TRL 6 in FY08.
- **Objectives:**
  - Cost - lowers System O&M costs - no hazardous fluids, easier system checkout
  - Safety - improves system safety - no hazardous fluids
  - System Responsiveness - improves system capacity and operability- faster turnaround
  - System Dependability - improves reliability and maintainability - easier system checkout, fewer or no sensors, robust motor and drive designs

Advanced EA Devices

- Background
  - For Launch vehicles, current SOA - hard switched motor drives, PM motors, RVDT and LVDT sensors, lower horsepower (40Hp - single string, 20 Hp- dual channel)- TRL 4
  - Use of EA's reduces maintenance costs, turn-around times and improves safety vs. conventional centralized hydraulic system
- Current status
  - Grants with University of Alabama and Montana State University in process
  - MSFC in start-up mode for linear motor work

Advanced EA Devices

- Major accomplishments:
  - New start

- Near term plans
  - Initiate grant with University of Alabama – Dynamic,compute-controlled test fixture (January 2001)
  - Initiate grant with Montana State University – Fuzzy logic motor control (January 2001)
  - MSFC begins linear motor work (November 2000)

- Task manager: Mary Ellen Roth

- Phone: (216)433-6288 Email: maryellen.roth@grc.nasa.gov

Hybrid Power Sources and Regeneration Technology for Electric Actuators

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For: Linda Taylor, GRC
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- Develop advanced proton-exchange-membrane fuel cell (PEMFC) technology as a replacement for existing alkaline fuel cell (AFC) technology
  - Enhanced safety
  - Higher power
  - Longer life
  - Lower weight
  - Improved reliability and maintainability
  - Higher peak-to-nominal power capability
  - Compatibility with propulsion-grade reactants
  - Reduced ground and mission operations
  - Potential for significantly lower cost

- Assemble an experienced NASA team to direct the effort
  - Team members GRC (lead), JSC, KSC, and MSFC
  - No vendor is clear leader in developing PEMFC technology for space applications
  - NASA has significant space fuel cell experience with Shuttle
  - NASA can direct design efforts to guarantee future vendor competition
    - Modular powerplant approach
  - NASA has most direct access to evolving RLV requirements

2nd Gen RLV Program: Technology Goals and Objectives

- Background:
  - Hybrid sources needed for advanced power systems due to high peak power demands of flight surfaces
  - Previous research by MSFC and GRC under the ELV System Modernization Program showed a hybrid source would reduce the overall size and weight of the power source – a supercapacitor would provide the peak power needed, while a battery would handle the nominal requirements

- Current Status/SOA:
  - Carbon and RuOx are most common electrode materials
  - Most devices are low voltage (<15V)
  - Maximum power density ~20kW/kg @ <1kJ/kg
  - Maximum energy density ~10kJ/kg @ <1kW/kg

Hybrid Sources and Regen. Energy

- Technology Goal:
  - Develop high power density, low ESR supercapacitors to provide peak power to EA loads and demonstrate the ability to recapture regenerative energy.

- Objectives:
  - Cost - Lower System O&M costs – no toxic materials
  - Safety - Improve System Safety – no toxic materials
  - System Responsiveness – improve system capacity – reduces weight of power source
  - System Dependability – improve reliability – high cycle life
  - Program goal of 40kW/kg @ 10kJ/kg

Hybrid Sources and Regen. Energy

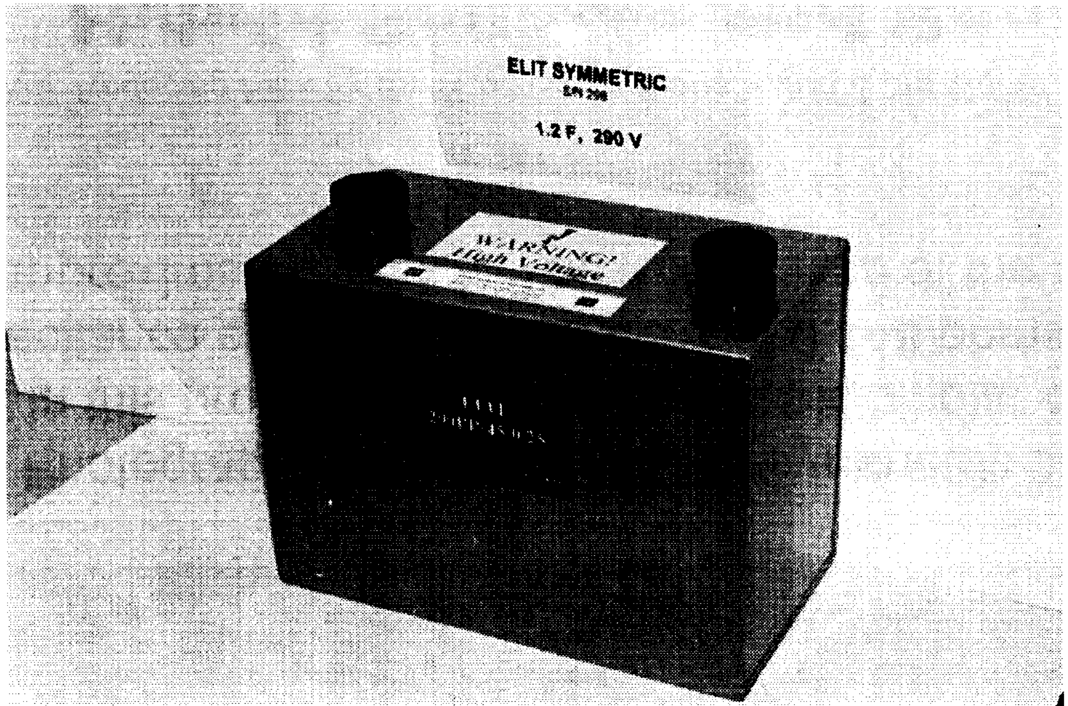

Figure 1: Photograph of one of the 290 V ELIT carbon-carbon capacitors (#298) developed in this program. It uses symmetric bipolar construction. Measured capacitance is 1.2 F. Total stored energy is approximately 50 kJ. The ruler on top of the capacitor is 6" long

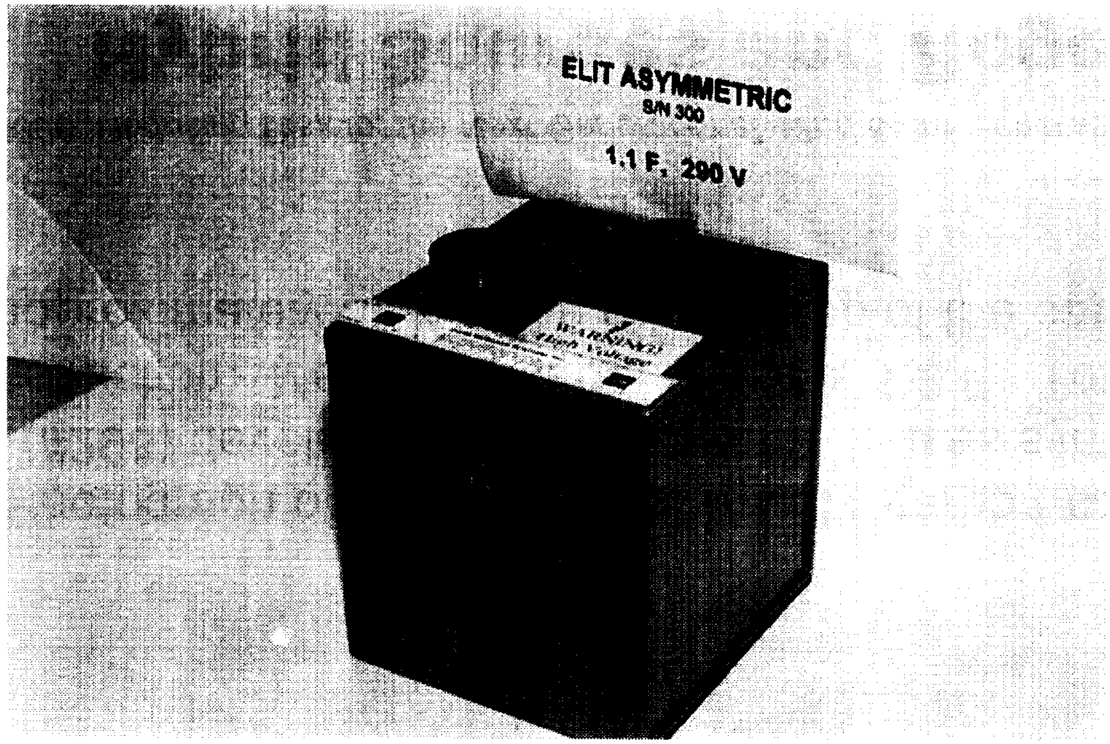

Figure 2: Photograph of the 290 V ELIT asymmetric capacitor developed in this program. It is of asymmetric bipolar construction with a capacitance of 1.1 F, and an ESR of 0.148 ohms. Stored energy is approximately 46 kJ. The ruler on top of the capacitor is 6” long.

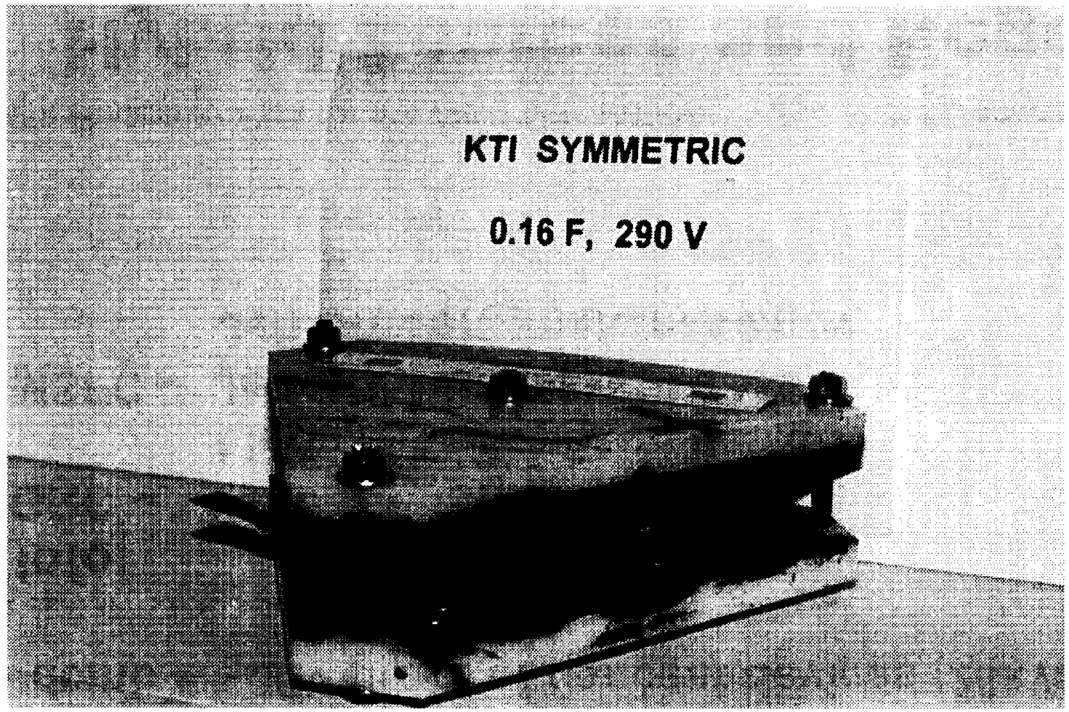

Figure 3: Photograph of the 290 V-rated KTI capacitor developed and delivered in this program. It has laboratory packaging. The capacitor uses a symmetric bipolar design with hydrated ruthenium oxide electrode materials. The device has a capacitance of 0.16 F. Total stored energy is approximately 5.4 kJ.

- **Major Accomplishments:**
  - **Under Bantam program, NASA has developed;**
    - Symmetric devices rated at 290 v, 5.9kW/kg at 2.6kJ/kg
    - An asymmetric device rated at 290 v, 17.3kW/kg at 5.6kJ/kg

- **Near Term Plans:**
  - **FY01 – demo a 290V device with an electric actuator (15kW/kg, 5kJ/kg)**
  - **FY02 – demo 4 – 30V proof of concept devices (25kW/kg, 8kJ/kg)**

- **Contact Info:**
  - **NASA GRC – Linda Taylor, (216)433-8478, Linda.M.Taylor@grc.nas.gov**
  - **NASA MSFC – Jeff Brewer (256)544-3345, Jeff.Brewer@msfc.nasa.gov**

Hybrid Sources and Regen. Energy

Intelligent Internal Thermal Control

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Eric.L.Golliher@lerc.nasa.gov

"ST Day 2000: Reducing Risk for the Next Generations"

- **Technology Goals and Objectives**
  - **Develop a Passive Method to Remove Heat from Power Electronics at the Chip Level**
    - Must Perform during Ascent, On-orbit, and Descent (Varying G-fields, μ-Gravity)
    - Achieve > 300 W/cm_
- **Background**
  - **Current State of the Art: Thermal Conduction through Solid Metal and Silicon and Large Motorized Fluid Pumps**
- **Near term plans**
  - **Initiate Investigation of New Concepts in Capillary Wick Design Using MEMS Technology**
- **Eric Golliher - NASA Glenn Research Center**
- **Thurman Henderson - University of Cincinnati http://www.mems.uc.edu/**

Intelligent Internal Thermal Control

First Concepts: Integrated Silicon Loop Heat Pipe on a Chip

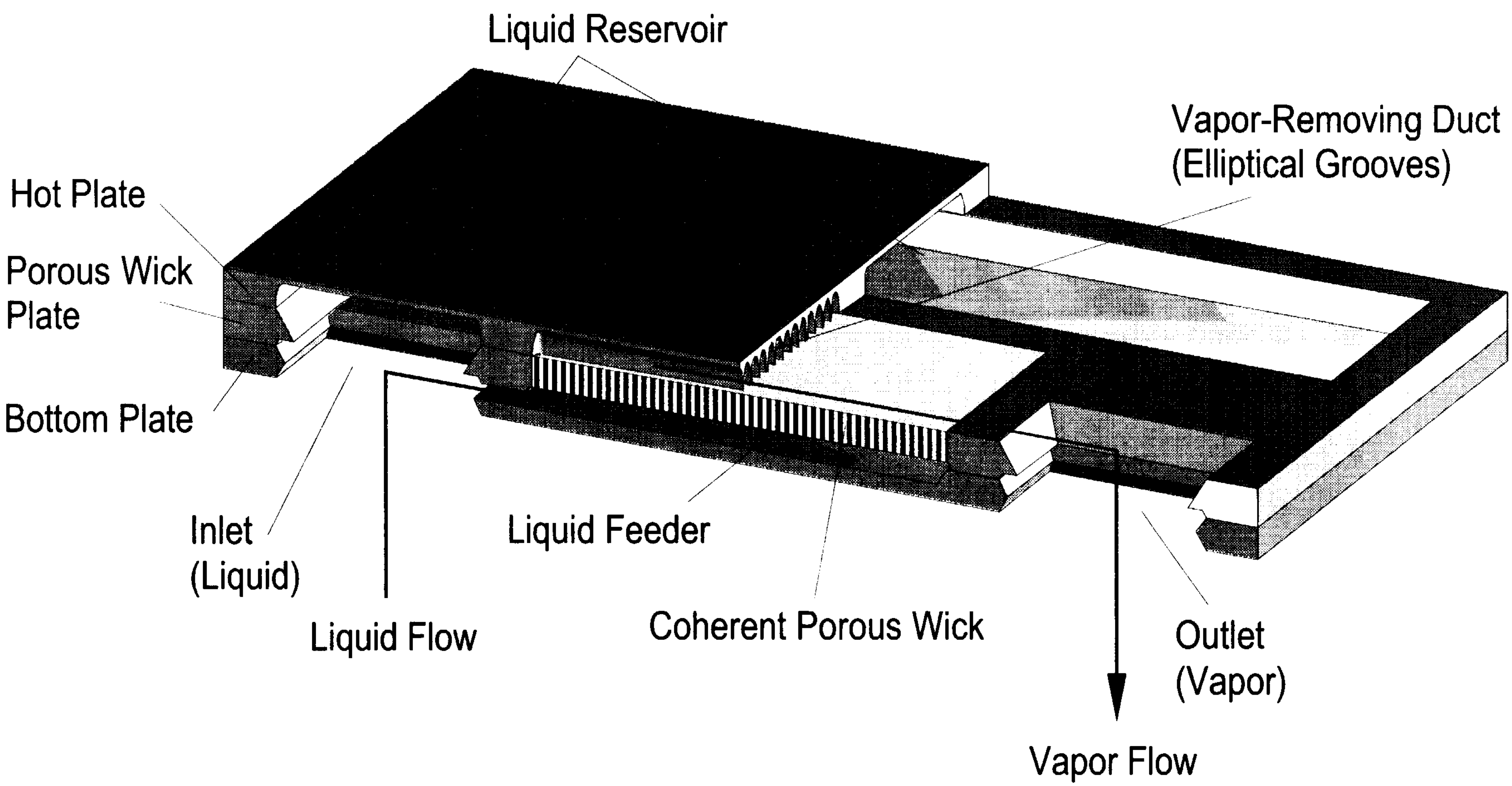
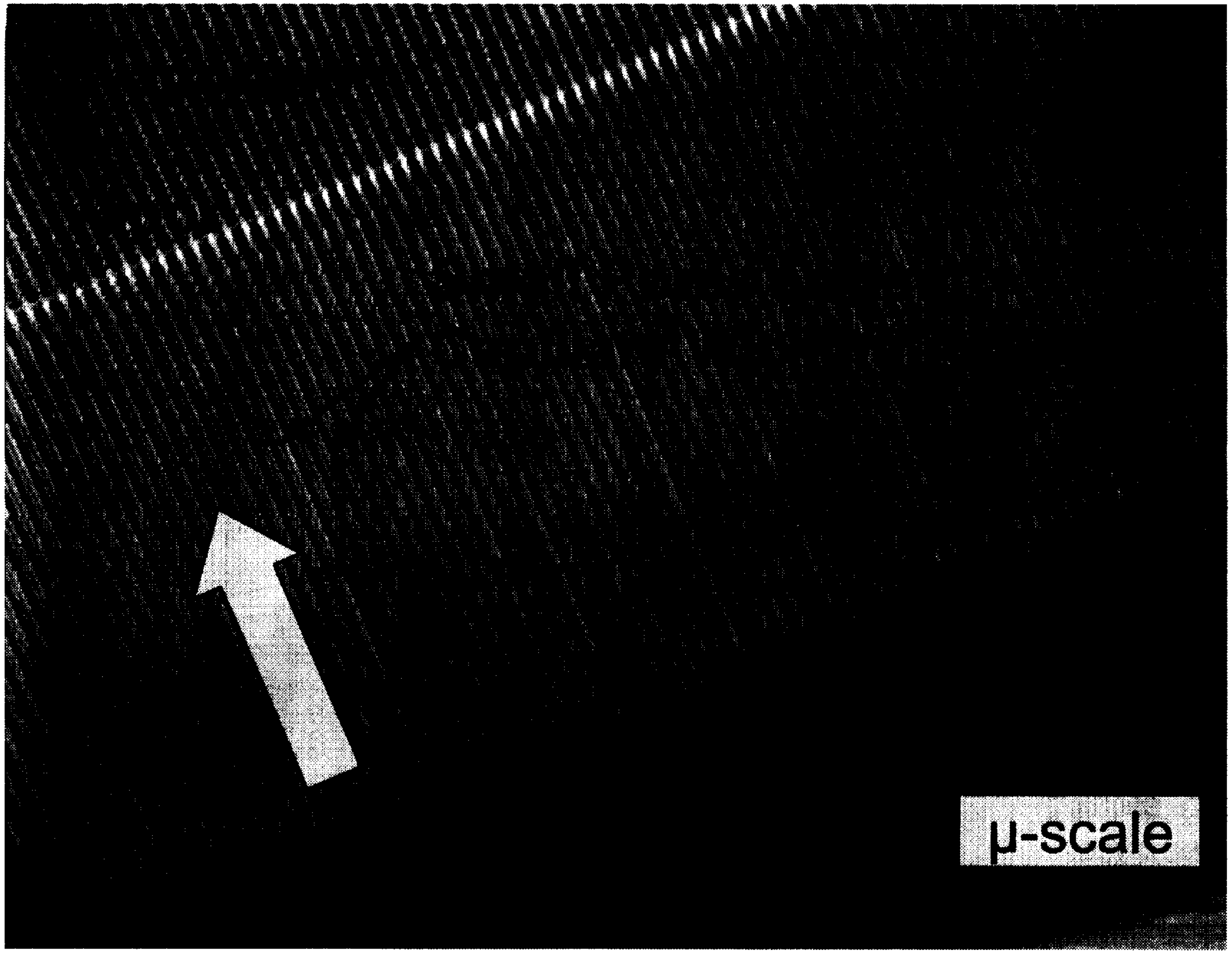


Fig. 1. Three-dimensional cutaway view of the integrated evaporator. Visible are the semi-elliptical vapor collecting grooves.

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Intelligent Internal Thermal Control

Close - Up : Silicon Wick Structure



Success Will Translate into Greater Reliability and Lower Maintenance

- We aim to develop two-phase evaporative heat transfer at the chip level, as opposed to the single-phase at the baseplate level, which is the current state of the art (SOA). This will allow the RLV thermal radiator heat transport loop to operate at a higher temperature than current SOA, because a chip is much warmer than the box baseplate. The advantage is that the higher-temperature RLV radiator will be smaller, because heat radiates as [Temperature] to the fourth power. Also, the system is passive and sealed, and therefore requires no mechanical pumps and no maintenance. Since the thermal path from chip to deep space is much more efficient, the chip temperature could be decreased slightly from SOA to provide higher reliability: (electronics' lower temperature => higher reliability).

Heritage

- The technology is derived from recent advances in spacecraft thermal management, where large "loop heat pipes" transport thousands of watts of heat passively. For example, the geostationary ~15 kWe Hughes HS702 satellite uses several loop heat pipes which carry 800 watts each and has a design life of nearly 15 years. The HS702 was the first operational use of loop heat pipes in a commercial American space vehicle (1999 launch). Our goal is to miniaturize the loop heat pipe technology to the chip level using MEMS technology. This technology can be incorporated into the 3rd Generation RLV thermal subsystem design.

Vehicle Subsystems Project, 2nd Gen RLV Program

Mike Skor

October 12, 2000

"ST Day 2000: Reducing Risk for the Next Generations"

Agenda

- **Vehicle Subsystems Project** — **Mike Skor**
  - Project Overview
  - Project Objectives/Management Structure
  - Project Planning Team
  - Points of Contact

- **PEM Fuel Cell Project (NASA-Led)** — **Mark Hoberecht**
  - Technology Goals and Objectives
  - Background
  - Benefits
  - Current Status
  - Major Accomplishments
  - Plans
  - Points of Contact

- NASA's highest priority goals for the 2nd Gen RLV Program are improved safety and reduced cost to orbit
  - 10x cheaper, < $1000/lb of payload to orbit
  - 100x safer, < 1/10,000 LOC

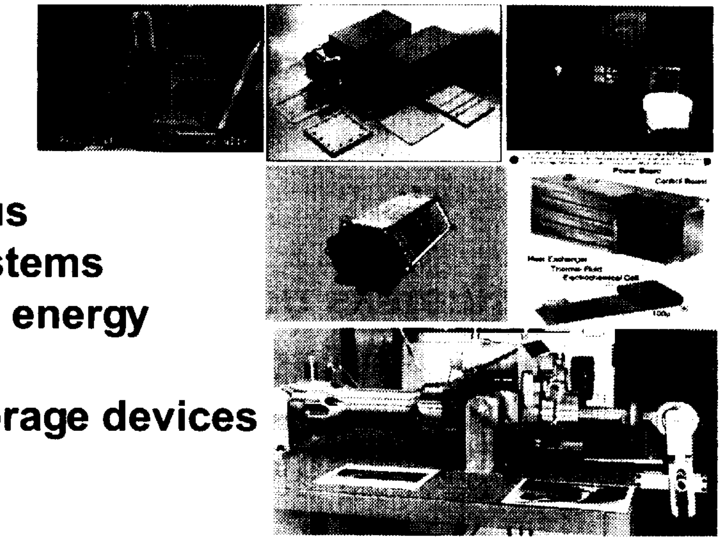
- Vehicle Subsystems Project is one of 9 Risk Reduction Projects in the 2nd Generation RLV Program

- Project key technologies first identified by the Industry/NASA Space Transportation Architecture Studies (STAS)

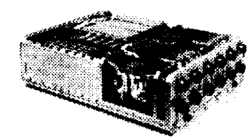
- Project key technology objectives are:
  - Robust, low-maintenance avionics with no active cooling requirements and autonomous rendezvous and docking systems
  - Low maintenance, high reliability, intelligent power systems
  - Low cost, low maintenance high horsepower actuation systems

Overview

- **Project objectives**
  - Consistent with system engineering processes --
  - Develop and demonstrate:
  - Advanced, integrated, micro avionics, autonomous
  - Rendezvous and docking, and mico-navigator systems
  - Advanced, lightweight, reliable power generation, energy storage, management and distribution systems
  - High power electric actuators and peak power storage devices
  - Other subsystems



- **Project Management Structure**



Steering Committee

Vehicle Subsystems
Mike Skor
GRC

Project Support

Avionics
Mark King
MSFC

Power
Nang Pham
GRC

Actuators
Nang Pham
GRC

Other
TBD

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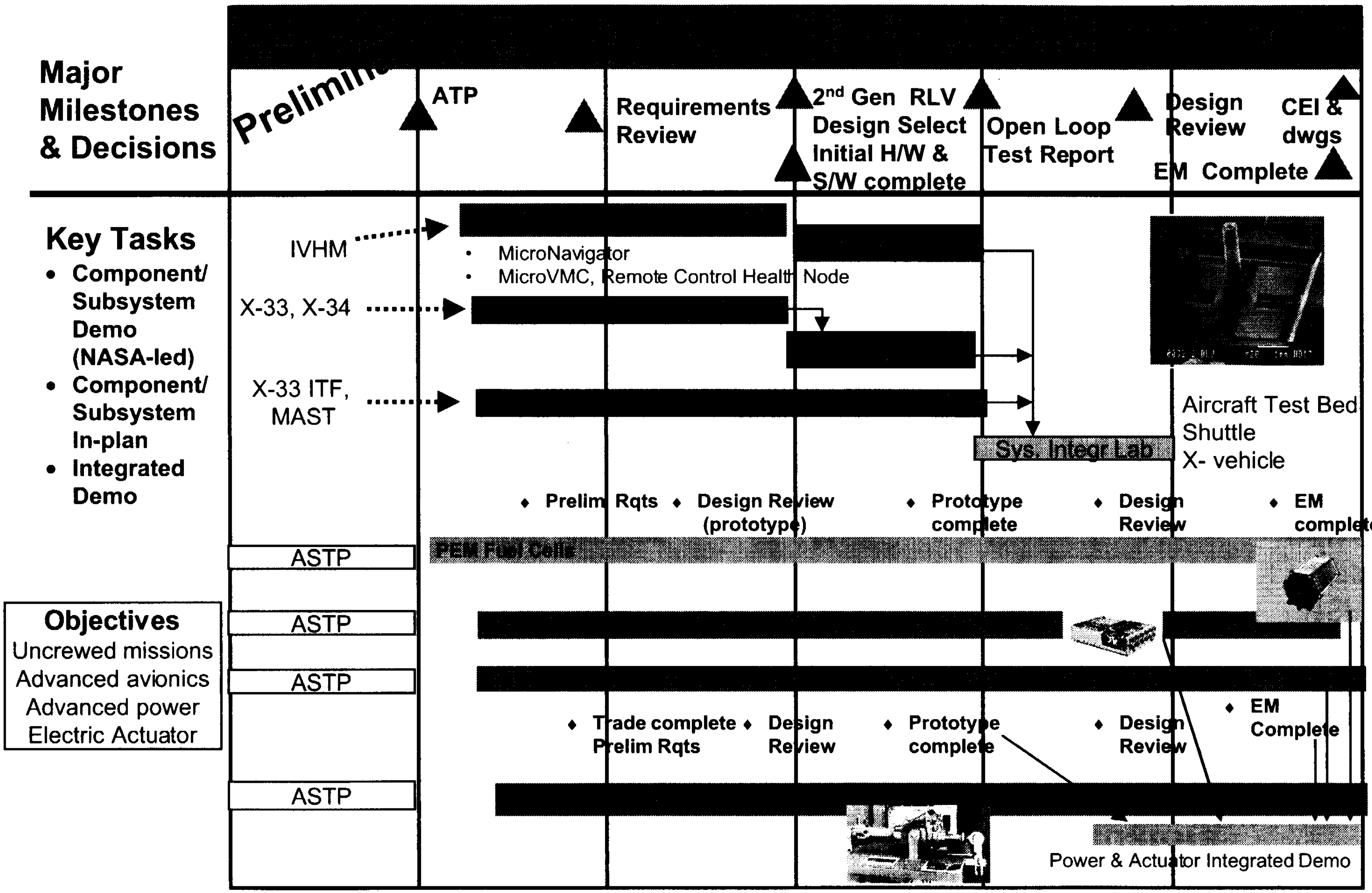
Project Objectives & Management Structure



"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Vehicle Subsystems Roadmap

Avionics		Power		Actuators	
Mark King (Lead)	MSFC	Nang Pham (Lead)	GRC	Nang Pham (Lead)	GRC
Jim Miller	MSFC	Mark Hoberecht	GRC	Jim Dolce	GRC
Bill Espinosa	GRC	James Dolce	GRC	Mary Ellen Roth	GRC
Brad Flick	DFRC	Norm Hagedorn	GRC	Landon Moore	JSC
David Jih	JSC	Steve Luna	MSFC	Steve Ryan	MSFC
Bill Kahle	ARC/MSFC	Lou Maus	MSFC	Brad Flick	DFRC
Wayne Schober	JPL	Jeff Brewer	MSFC	Steve Jensen	DFRC
				Karla Bradley	JSC

"ST Day 2000: Reducing Risk for the Next Generations" - 2nd & 3rd Generation Vehicle Subsystems

Project Working Groups

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Points of Contacts

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Linda Taylor	216-433-8478	Linda.M.Taylor@grc.nasa.gov

Vehicle Subsystems Project, 2^{nd} Gen RLV Program

PEM Fuel Cell Project
(NASA-Led)

Mark Hoberecht GRC

Other Team Members

Karla Bradley	JSC
Patricia Gladney	KSC
Lou Maus	MSFC

- **Develop advanced proton-exchange-membrane fuel cell (PEMFC) technology as a replacement for existing alkaline fuel cell (AFC) technology**
  - **Enhanced safety**
  - **Higher power**
  - **Longer life**
  - **Lower weight**
  - **Improved reliability and maintainability**
  - **Higher peak-to-nominal power capability**
  - **Compatibility with propulsion-grade reactants**
  - **Reduced ground and mission operations**
  - **Potential for significantly lower cost**

- **Assemble an experienced NASA team to direct the effort**
  - **Team members GRC (lead), JSC, KSC, and MSFC**
  - **No vendor is clear leader in developing PEMFC technology for space applications**
  - **NASA has significant space fuel cell experience with Shuttle**
  - **NASA can direct design efforts to guarantee future vendor competition**
    - Modular powerplant approach
  - **NASA has most direct access to evolving RLV requirements**

Technology Goals and Objectives

- NASA first developed PEMFC technology for Gemini in the 1960's
  - Low power
  - Poor performance
  - Marginal reliability
  - High cost

- NASA developed AFC technology for Shuttle in the 1980's
  - Higher power
  - Excellent performance
  - High reliability
  - High cost

- Commercial market spent hundreds of millions of dollars in the 1990's to advance PEMFC technology for automotive and residential applications; technology spin-off *to* NASA
  - Very high power
  - Excellent performance
  - Very high reliability
  - Very low cost potential (similar to electronics and telecommunications industry)

Background

- NASA team (JSC, GRC, KSC) proposed PEMFC technology for Shuttle Upgrade Program in mid 1990's
  - JSC awarded study contracts to two potential vendors (AlliedSignal, IFC)
  - PEMFC technology showed greatest long-term benefits
  - Improved AFC technology selected because of lower up-front costs to modify AFC than replace entire fleet with PMCFC

- GRC teamed with AlliedSignal (now Honeywell) on successful PEMFC stack development proposal for RLV; part of NRA 8-21 in 1998
  - 26-month effort
  - Component development
  - Stack design
  - Final end-product: 5-kW, 30-V modular PEMFC stack

Background Continued

- Safety/Reliability
  - Reduced hazardous materials in fuel cell stack (no KOH, no asbestos)
  - Reduced critical failure modes (hydrogen over-pressurization, electrolyte wash-out)
  - Graceful performance degradation
- Durability/Supportability
  - Elimination of inherent corrosion
  - Reduced ground servicing from enhanced IVHM
- Cost
  - Total DDT&E cost estimated at $20 - $30 million for PEMFC (TRL level 4 to 8)
  - Projected flight powerplant costs: PEMFC < half AFC
  - Evolving and highly competitive commercial market to drive down future stack costs
  - Reduced life-cycle costs
    - Longer life powerplants
    - Improved logistics (bench-top maintenance)

Benefits (PEMFC vs. AFC Technologies)

- PEMFC commercial vendors nearing market readiness for H_2/air systems
  - Full production for automotive model vehicle line by mid-decade
  - Residential fuel cell unit within several years

- Commercial PEMFC technology not directly suitable for space applications
  - Water management issues in zero-g environment
  - Materials compatibility issues for pure O_2 reactant

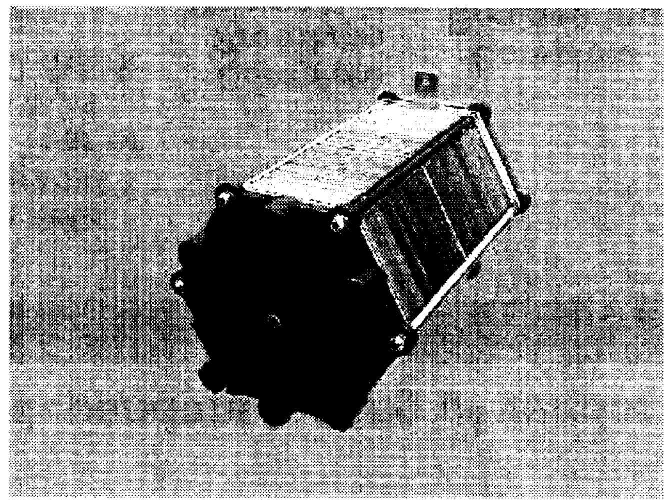
- ERAST program developing regenerative fuel cell (RFC) energy storage based on PEM fuel cell and water electrolysis technology
  - RFC is enabling energy storage technology for high-altitude aircraft and Lunar/Mars bases because of long cycle times (e.g. 12 hrs. daylight/ 12 hrs. darkness)
  - Team members Dryden – lead, GRC, and AeroVironment

- NRA 8-21 PEMFC stack development nearing completion

- NASA-led PEMFC powerplant development proposal selected for 2nd Gen RLV Program

Current Status

- NRA 8-21 PEMFC stack development nearing completion
  - Successful component development
    - Membrane/electrode assemblies, bipolar plates, current collectors
  - Characterization testing of 5-kW modular stack underway
    - Pure O_2 performance ≥ air performance



  - Life testing to be incorporated into 2nd Gen RLV Program
    - Integrated stack/ancillary hardware test at JSC

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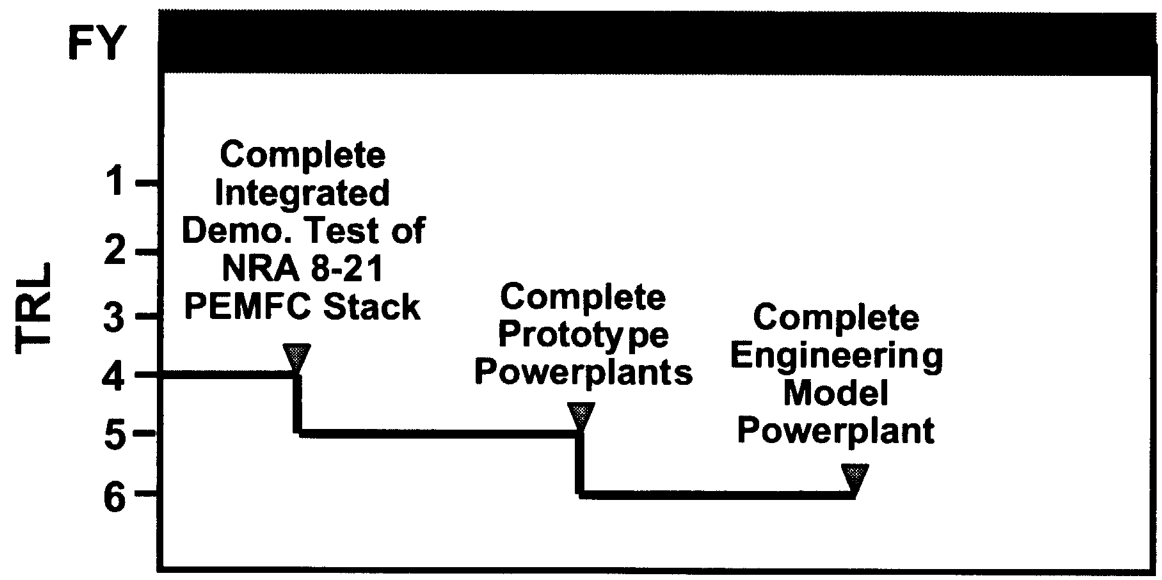
Major Accomplishments

- NASA-led PEMFC powerplant development proposal selected for 2^{nd} Gen RLV Program
  - Experienced NASA team (GRC – lead, JSC, KSC, MSFC)
  - NASA develops system requirements and design specifications
  - Contract awards allow vendor competition for hardware development
    - Prototype powerplant advances TRL from 4 to 5; two contract awards
    - Engineering model powerplant advances TRL from 5 to 6; single contract award
  - NASA conducts independent testing of vendor hardware



Plans

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Points of Contact

THANK YOU

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